Low Amplitude Fatigue Performance of Sandstone, Marble, and Granite under High Static Stress

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Abstract: Fatigue tests under high static pre-stress loads can provide meaningful results to better understand the time-dependent failure characteristics of rock and rock-like materials. However, fatigue tests under high static pre-stress loads are rarely reported in precious literatures. In this study, the rock specimens were loaded with a high static pre-stress representing 70% and 80% of the UCS, and cyclic fatigue loads with a low amplitude (i.e., 5%, 7.5% and 10% of the UCS) were applied. The results demonstrate that the fatigue life decreased as the static pre-stress level or amplitude of fatigue loads increased for all rock types, and the high static pre-stress affected the fatigue life greatly when the static pre-stress was larger than the damage stress of rocks in uniaxial compression test. The accumulative fatigue damage exhibited three stages during the fatigue failure process: crack initiation, uniform velocity, and acceleration, and so the fatigue modulus showed an "S-type" change trend. The lateral strain and volumetric strain had a much higher sensitivity to the cyclic loading and could be used to predict fatigue failure characteristics, and it was found that volumetric strain $\varepsilon_v = 0$ is a threshold for microcracks coalescence and is an important value for estimating the fatigue life.

Keywords: High static pre-stress; Fatigue loading; Low amplitude; Mechanical properties.

Nomenclature:

σ_s	Static stress	σ_d	Dynamic stress
σ	Stress	ε	Strain
UCT	Uniaxial compression test	t	Loading time
UFT	Uniaxial fatigue test	V_L	Wave velocity of rock specimen before testing
σ_1	The major principal stress	σ_3	The minor principal stress
σ_2	The intermediate principal stress	W_f	Wave form
σ_{ucs}	Uniaxial compressive strength (UCS)	T_{fl}	Fatigue life
σ_{max}	Peak value of fatigue cyclic loads	ε_{max}	Axial strain on peak value of fatigue cyclic loads

σ_{min}	Valley value of fatigue cyclic loads	ε_{min}	Axial strain on valley value of fatigue cyclic loads
σ_{mea}	Average value of fatigue cyclic loads	ε_{mea}	Axial strain on average value of fatigue cyclic loads
μ	Poisson's ratio of elastic stage in UCT	μ_c	Poisson's ratio during the whole testing process
σ_{fs}	Fatigue strength	f	Frequency of fatigue loads
n	Number of fatigue loads	ε_a	Axial strain
ε_l	Lateral strain	ε_v	Volumetric strain
E_y	Young's modulus in UCT	E_s	Secant modulus in UCS test
σ_x	Initial stress point of elastic stage in UCT	ε_x	Initial strain point of elastic stage in UCT
σ_y	End stress point of elastic stage in UCT	ε_y	End strain point of elastic stage in UCT
σ_{50}	Stress level with value equals to half of σ_{ucs} in UCT	ε_{50}	Strain point at the σ_{50} in UCT
E_{dtm}	Dynamic tangent modulus	E_{dsm}	Dynamic secant modulus

1 Introduction

The construction of subsurface spaces was expected to exhibit explosive growth for purposes such as mine excavation as well as hydroelectric station, oil and gas storage plant, multi-purpose tunnel, nuclear power station, nuclear waste repository, and compressed air energy repository development. Some researchers have focused on the time-dependent response of specific rock types to stress conditions to investigate each type's creep and fatigue properties [1-3]. The stress condition and carrying capacity of rocks are key factors affecting their failure. The stress conditions can be classified into three types [3-5]—namely, uniaxial static, biaxial static, and triaxial static in addition to dynamic stress. Uniaxial static and dynamic stress are considered for slender isolated pillars or surrounding rocks at the intersection of underground crossed roadways (Fig. 1a), whereas biaxial static and dynamic stress are considered at the surrounding rocks near the boundaries of underground spaces (Fig. 1b). The triaxial static plus dynamic stress occurs with rocks that far away the frontiers of excavations (Fig. 1c). Static stresses are primarily generated due to tectonic and gravitational forces, whereas dynamic stresses are induced mostly by earthquake, rock burst, and rock blasting or drilling [4, 6-7].

Fatigue failure is caused by long-term cyclic repetitive loads that have a peak stress level lower than the static strength of the rocks. According to previous studies, the main factors affecting rock fatigue behaviour are rock lithology, water content, and cyclic loading characteristics (frequency, amplitude, wave form, and loading stress level). The wave forms (w_f) used for repetitive loads in fatigue tests include sinusoidal waves [8-18], triangular waves [8, 19-25], and square waves [23-24]. Previous study results indicate that the strain increment caused by the sinusoidal loading waveform is larger than that induced by the triangle loading waveform, and the applied input energy by sinusoidal loading waveforms was larger than that induced by triangle loading waveforms. The literature review revealed that the most frequently used loading frequency was in the range of 0.1 – 10 Hz, in accordance with the frequency of waves generated during earthquakes, rock bursts, and blasting [19, 26].

Previous studies on rock fatigue behaviour focused on the fatigue loading parameters effect, and varied results have been obtained. For example, it was found that fatigue crack propagation occurred in the loading direction, and crack opening occurred in the lateral direction [1]. By comparing the change trends of the axial and lateral strains, it was found that the lateral strain in rock specimens develops more rapidly than axial strain during fatigue loading [8, 15]. A 'critical axial strain' was identified, and when the axial strain of a specimen during a fatigue test reaches this value, failure is imminent [10, 12-13, 15, 27]. This critical axial strain corresponds to the strain at the post failure part of the static stress-strain curve with the same stress level as the maximum cyclic loading stress level [12-17, 27]. Strain at the failure point was found to increase as the number of loading cycles increased and was dependent on the strain rate; hence, it decreases with increasing strain rate [22].

As the mentioned literature reveal, determining the fatigue properties of rocks in laboratory settings has gained value over recent decades. Most of these studies have focused on the effects of certain variables on rock fatigue behaviour, such as frequency, peak value, amplitude, water content, confining pressure, and wave form, etc. [23, 28]. The commonly used stress state during the fatigue tests was the uniaxial compressive stress state [5-6, 29] because of the lowest carrying ability of rocks under uniaxial stress state. Owing to it being hard to fracture rocks under a constant confining pressure, the conventional triaxial fatigue tests have been rarely studied [30-33]. For example, the conventional triaxial fatigue tests were performed to evaluate the effects of the confining pressure on the fatigue failure characteristics of sandstone specimens and reported that strain at failure increased with increasing confining pressure and three steps for the fatigue damages were also identified [31-32]. The fatigue failure properties of rocks in uniaxial fatigue tests and conventional triaxial fatigue tests have essentially the same conclusions.

Before rock failure, the rocks are subjected geo-stresses (as shown in Fig. 1), and most previous studies have ignored the effect of crustal stress in field practice on the failure of rocks, especially for the time-depended failure of rocks, such as fatigue failure. This can lead to misunderstandings regarding the fatigue failure properties of deeply buried rocks. Therefore, to evaluate the fatigue behaviour of underground space surrounding rocks that are subjected to cyclic fatigue loading, the effects of the pre-stress state cannot to be neglected. In this study, a series of uniaxial fatigue tests were conducted on high static pre-stressed rock specimens, and rock fatigue characteristics were systematically studied. The static pre-stress was applied at a quasi-static loading rate to the rock specimens firstly, which is to simulate the crustal stress existing originally.

2 Experimental Methodology

2.1 Rock specimens

In this study, three types of rocks, i.e. sandstone, marble, and granite, were evaluated.

Cylindrical rock specimens were prepared with a height to diameter ratio of 2 and an average diameter of 50 mm (Fig. 2a). Using the International Society for Rock Mechanics suggested methods [5], the basic physical and mechanical parameters, i.e. uniaxial compressive strength σ_{ucs}, Young's modulus in uniaxial compression test (UCT) Ey, Poisson's ratio in uniaxial compression test μ, and wave velocity V_L, were determined and summarised in Table 1. The values of the basic parameters of rocks were used as a reference to arrange the subsequent cyclic fatigue dynamic tests.

For the basic mechanical parameters, granite with an average σ_{ucs}=112.5 MPa and Ey=35.45 GPa had the highest strength and elastic modulus, whereas the sandstone with an average σ_{ucs}=31.8 MPa and Ey=8.60 GPa had the lowest strength and elastic modulus. The reverse result was obtained for the Poisson ratios; granite and sandstone specimens had the lowest and highest values, respectively. For rock materials, the higher the wave velocity V_L is, the lower the porosity is, and the higher the density is. In this study, the V_L of sandstone was the smallest, that of granite was the largest, and that of marble is in between the two. It can be inferred that granite had the smallest porosity, sandstone had the largest porosity, and marble had the medium porosity.

Petrographic thin section analyses of the three rock types (Fig. 2a) were conducted, and the main conclusions were as follows. The granite was coarse-grained and primarily composed of feldspar (35–41%), quartz (40–46%), biotite (15–25%), and a small amount of muscovite and other minerals. The marble was fine-grained and contained magnesite (40–50%) and calcite (40–45%). The sandstone was fine-grained and primarily composed of quartz (50–70%), feldspars (20–30%), rock fragments (15–20%), and a small amount of muscovite, biotite, and other minerals.

2.2 Testing techniques

In this study, a closed-loop servo-controlled testing system (ZTR 203) was used, as shown in Fig. 2b. The maximum axial loading capacity is 1000 Kn, and the loading precision is ± 0.5%. In addition, the system can also apply cyclic fatigue loads with different frequencies ranging from 0–70 Hz. The ZTR 203 can perform various unidirectional loading tests such as the uniaxial compression test, uniaxial creep, and fatigue test. The axial and lateral strain of rocks during the fatigue loading process were measured using a novel extensometer apparatus, which is coupled with four axial linear variable differential extensometers and four lateral linear variable differential extensometers (Fig. 2c-d).

The working principle of the extensometer apparatus is described as follows: with the loading of axial stress σ_1, the axial height of rock specimens decreases because of the downward motion of the ladder-shaped steel platen, and the lateral length of rock specimens increase because of the lateral dilatation, so the axial and lateral extensometers rotate strain along the fixed point, and the strain gauges buried in the axial and lateral extensometers generate data because of their bending force. The data of strain gauges in the axial and lateral extensometers have linear relationship with the axial strain and lateral stain of rock specimens, respectively. The linear relationships are determined by metrological calibration. The precision of the axial and lateral extensometers is ± 0.5%. The test data can be obtained and stored using the instrument software.

2.3 Loading procedures

To examine the effects of the static pre-stress, maximum stress value, and amplitude of the cyclic loads on the failure characteristics of the rocks, a series of uniaxial fatigue tests (UFT) with the stress path shown in Fig. 3a were designed and conducted. The detailed testing procedure was as follows. First, the static pre-stress was applied to the specimens up to a considered pre-static level with a loading rate of 30 kN/min, and the static pre-stress equalled to the valley value of the cyclic loading. Then, the cyclic loading was initiated using the defined amplitude, wave form, and loading frequency. In this study, different pre-stress levels and amplitudes of sinusoidal fatigue loads with frequencies of 5 Hz were employed.

The damage stress σ_{cd} of rocks is about (70-90) % of their σ_{ucs} in uniaxial compression test, which denotes the unstable crack growth in rocks [5]. Based on theσ_{cd} of rocks, the pre-stress level was set from 70% to 80% of the σ_{ucs} in this study, and was not as that shown in Fig. 3b. It is also reported that the vertical stress of field rocks increasing 27MPa with the buried depth each increasing 1 km [34], and the vertical stress increase by a concentration factor of 2 or above after underground engineering excavation. So, the pre-stress level in this study denoted that the buried depth of underground surrounding rocks was ranged from 0.41 km to 1.67 km, which is the depth most deep underground engineering buried at present.

Furthermore, the $\sigma_{\max}$ of fatigue loads was considered as 90% to 95% of the σ_{ucs} in order to avoid the total stress on the specimens beyond their σ_{ucs} (Fig.3c). The loading amplitude was kept at a low level. The detailed values of the different applied stresses on the rocks are presented in

Table 2. In most tests, the specimens failed, but some of the specimens did not fail even after four hours of cyclic loading. The data, including the force, displacement, axial strain, lateral strain, and loading time, were recorded during each cycle. For a better understanding and to compare the results, all specimens were categorized in 3 groups of A, B, and C, based on the applied stress scenario.

3 Experimental results and discussion

3.1 Stress thresholds

The stress-strain (σ-ε) curve of rocks in uniaxial compression test can be divided into the four stages: Natural crack closure stage, Crack initiation and elastic stage, Stable crack expansion stage and Unstable crack expansion stage [5]. The stress thresholds of adjacent stages are the closure stress σ_{cc}, the initiation stressσ_{ci}, the damage stressσ_{cd} and the peak stress (the uniaxial compressive strength) σ_{ucs}, as shown in Fig.4a.

The$\sigma_{cc}$and $\sigma_{ci}$are associated with the onset of crack initiation and stable crack growth, respectively. The σ_{cd} indicates the onset of the unstable crack expansion, which corresponds to the axial stress value at the volumetric dilatancy point. Theσ_{ucs} is the peak value of the axial stress before specimen failed. The σ_{cd} andσ_{ucs} are also called "long-term strength" and "short-term strength" of rocks, respectively. In this study, the stress thresholds of granite, marble, and sandstone are shown in Fig.4b-d, andσ_{cd} for granite, marble, and sandstone are 80.7%, 78.7%, and 68.3%, respectively.

3.2 Fatigue life

Fatigue life (T_{fl}) is the number of fatigue loading cycles corresponds to failure. It is an important parameter that is affected by the static pre-stress level and peak value of fatigue load. The T_{fl} values for the sandstone specimens were approximately equal to or larger than 10^4 (from 8997 to 33871 cycles). The marble specimens in groups A and B and the granite specimens in group A did not suffer final failure after 4 hours of fatigue loading. The average T_{fl} value of the marble specimens in Group C under fatigue loads with σ_{max} = 95% of the σ_{ucs} was only 85 cycles. The T_{fl} of the granite specimens in group B ranged from 3956 to 3136 cycles. The average T_{fl} value of the granite specimens in group C under fatigue loads with σ_{max}=95% of the σ_{ucs} was only 37 cycles. The obtained results on the fatigue life and its affecting parameters are summarized below.

(1) The tests results indicate that the fatigue loads with a low amplitude had only a limited influence on the crack expansion when the value of the pre-stress was set at 70% of the σ_{ucs}. For sandstone, the damage stressσ_{cd} was lower than 70%; therefore, all sandstone specimens suffered final failure in uniaxial fatigue tests. Theσ_{cd} of the marble and granite specimens was larger than 80%, and the specimens under fatigue loads with a $\sigma_{\min}$ =70% did not fail after 4 hours of cyclic loading. When the static pre-stress were over 80% of the σ_{ucs}, the number of unstable cracks in the rock specimens patently increased and the T_{fl} quickly decreased, as shown in Fig.5b-d. Under the same peak value of fatigue loading, the amplitude of fatigue loading in Group A was bigger than that in Group B, while the T_{fl} of specimens in Group A was shorter than that of specimens in Group B, it seems that the amplitude effect on T_{fl} didn't work.

(2) Under cyclic loads with a $\sigma_{\max}$ = 90% of the σ_{ucs} and $\sigma_{\min}$ = 70% of the σ_{ucs}, the granite and marble specimens did not fail after 4 hours of fatigue loading. This may be related to the static pre-stress being lower thanσ_{cd} and low peak value of fatigue loads. Under cyclic fatigue loading conditions with a $\sigma_{\max}$ = 90% of the σ_{ucs} and a $\sigma_{\min}$ = 80% of the σ_{ucs}, sandstone and granite exhibited a clear decrease in the fatigue life while the marble specimens did not fail. Because the peak value of fatigue loading was constant with that of the specimens in group A, increasing the valley values led to increase the time that the specimens were exposed to high static stress. So it is can be inferred that the main reason of fatigue life decreasing is more unstable cracks induced by the static pre-stress before fatigue loading.

(3) Based on their rock lithology, the granite is a coarse-grained igneous rock, and contains several kinds of minerals with different hardness. However, marble is a fine-grained metamorphic rock, and the mineral composition is also simple. Some microcracks exist among the grain boundaries for granite and granite is easier get finally failure than marble under similar fatigue loading condition (Fig.3a). Under fatigue loads with a $\sigma_{\max}$ = 95% of the σ_{ucs}, the T_{fl} of the marble and granite specimens showed dramatically decreases, whereas the sandstone specimens showed slight decreases. The sandstone rocks are highly porosity and ductile, therefore, the fracture evolution in the sandstone specimens occurred slowly.

(4) The decreasing T_{fl} values of specimens from group B to group C indicates that the effect of the peak value of fatigue loading is also remarkable. In fact, it can be concluded that when the peak stress level increase, the fatigue life decreases. This result is consisted with previous studies [35-37], as shown in Fig. 5. In this study, when the $\sigma_{\max}$ reached 95% of the σ_{ucs}, the T_{fl} quickly

decreased, especially for the brittle rocks such as the granite and marble in this study.

3.3 Fatigue strain

The stress–strain curves of the different rock specimens in the uniaxial compression tests and fatigue tests are shown in Figs. 6-8. The ε_{max} and ε_{min} values exhibited the same change trends and both increased corresponding with the increased stress levels. Every cycle of fatigue loading-unloading could lead to the generation of plastic or residual strain and strip-shaped hysteresis loops that are limited in the range of the maximum and minimum applied loads. The development of the regular hysteresis loops went from sparse to dense and then from dense to sparse. During the initial fatigue loading period, the cracks inside the specimens were first closed and the hysteresis loops appeared from sparse to dense. With the increasing accumulative damage, the hysteresis loops gradually changed from dense to sparse. In some cases of this study, because of the high pre-stress effect, the pre-existence cracks were closed before the cyclic loads were applied and therefore, the variation of the strain from sparse to dense was not clearly observed. Furthermore, the lateral strain and volumetric strain also exhibited similar change trends to the axial strain. The ‘sparse – dense – sparse’ change process of the strain also proved that there was an inverted S-shaped nonlinear fatigue cumulative damage model in the rocks under fatigue loads [38]. The primary stage occurred when the strain increased from cycle to cycle with a decelerating rate, followed by a steady stage of linear increases in the strain, and culminating in an accelerated stage of strain increases up to failure. The result was also supported during the conventional triaxial fatigue test [30-33].

For the specimens without final failure after 4 hours of fatigue loading, the axial, lateral, and volumetric strains slowly developed and did not reach the values of the post-peak strain corresponding to the σ_{max} in the uniaxial compression tests as shown in Fig. 6a-c and Fig. 7a-f. A critical value for the axial, lateral, or volumetric strains was identified for most of the rock specimens, and when the fatigue strains reached this critical value, the specimen failure was more likely to occur, as shown in Figs. 6g-i, 7g-i, and 8. This critical value was the post-peak strain in the uniaxial compression test corresponding to the σ_{max}. Of course, due to the individual differences between the rock specimens, the critical value of a sample may be different from the failure threshold strain of another sample and cannot exactly determine the failure of all rock specimens, such as DG-6 (Fig. 6d-f). Consequently, it can be concluded that the fatigue failure of most of the rock specimens was controlled by their perfect stress-strain curves and can be predicted by the post-peak strain corresponding to the σ_{max} in the monotonic tests.

The volumetric strain versus the axial strain curves are shown in Fig. 9. Under such a special fatigue loading condition, the volumetric strain at the initial point of the applied cyclic loads was a main factor affecting the fatigue behaviour of the rocks. Larger induced volumetric strain by the pre-stress loading led to an enhanced failure in the rocks. For the granite and marble specimens, the ε_v value of the unbroken rock specimens, such as DG-1, DG-2, DM-1, DM-2, DM-3, and DM-4 were larger than 0 (compression area) before the cyclic loading. In addition, the expansion velocity of the marble cracks was much lower than that of the granite because the nucleation of the cracks is more difficult to achieve than the growth of the cracks themselves. It was forecasted that the rock specimens would achieve final failure if the time of the fatigue loads was prolonged. For the failed specimens of the different rock types, ε_v was below 0 and reached a dilation area. Therefore, the stress level corresponding to $\varepsilon_v = 0$ was an important parameter on the failure characteristics of the rocks under fatigue loads with low amplitude and number of cycles lower than 10^5.

In this study, the Poisson ratio (μ_c) refers to the ratio of the lateral strain to the axial strain during the entire testing process and the μ_c of the rock specimens during the different tests are shown in Fig. 10. The Poisson ratios of the specimens in the static loads were mostly less than the values under cyclic loads. This was observed because of the accumulation of lateral strain during cyclic loading. The increases in the Poisson ratios increased considerably with the decreasing fatigue life and increasing maximum stress level. The variation trend of μ_c under cyclic loading conditions was similar to that of the fatigue strain, i.e., an *S*-shaped nonlinear development model that could be divided into three stages: primary stage, steady-state stage, and rapidly expanding stage. According to Fig. 10, for the unbroken rock specimens, the rapidly expanding stage was not observed.

3.4 Fatigue modulus

In the uniaxial compression tests, the Young modulus (E_y) and the secant modulus (E_s) are often used to describe the deformation behaviour of rocks [39]. However, two additional types of dynamic moduli including the dynamic tangent modulus (E_{dtm}) and the dynamic secant modulus (E_{dsm}) are commonly used as fatigue damage variables. The calculation methods of the mentioned types of modulus are shown in Fig. 11. The E_{dtm} and E_{dsm} values in the loading and unloading parts of each fatigue loading cycle appear with different values.

The measured modulus values for the tested specimens are shown in Table 3. In the uniaxial compression strength tests, the values of E_s were lower than those of E_y of all specimens. The E_{dtm} and E_{dsm} values in uniaxial fatigue tests were larger than E_s and E_y because of the higher loading rate. The two types of modulus values in the loading part were smaller than that in the unloading part of each cycle due to occurrence of damages and residual strain during the loading phase. Inspection of Table 3 shows that the E_{dsm} was larger than E_s for the sandstone specimens, whereas the E_{dsm} of the marble and granite specimens was smaller than the E_s. Also, the E_{dtm} values for of all the rock specimens were larger than the E_y values of the rocks. Furthermore, the E_{dsm} of the failed specimens during the loading stage were smaller than the values during the unloading stage, while for the unbroken specimens, the E_{dsm} of the loading and unloading stages had similar values overall.

The change trends of the E_{dtm} and E_{dsm} values for the rock specimens under different loading conditions with increasing numbers of loading cycles are shown in Figs. 12 - 13. In general, the E_{dtm} and E_{dsm} had similar changing trends but were different in magnitude. There was an obvious reduction in the E_{dtm} and E_{dsm} values with the increasing number of loading cycles and could also be divided into three clear stages for the failed specimens as shown in Figs. 12 - 13 and discussed herein. 1) Primary stage: the residual strain during the initial few cycles rapidly increased and the E_{dtm} and E_{dsm} values decreased with a relative high speed. 2) Steady-state stage: the E_{dtm} and E_{dsm} values decreased at a low slope constant rate. 3) Rapidly expanding stage: the E_{dtm} and E_{dsm} values sharply decreased and rock failure immediately followed. This stage is related to the coalescence of the developed cracks during the previous cycles. The second stage of damage for the secant modulus increased with increasing maximum load.

In this study, there was a slight difference in the change trends of the E_{dtm} during the primary stage of the loading and unloading curves as shown in Fig. 12. The E_{dtm} values during the loading part of fatigue loads became larger during the initial period of fatigue loading (Fig. 12 a, c, e), then remained constant and decreased with the accelerating rate. The increase during the first few cycles was due to the closing and elimination of the pores and the pre-existence micro cracks during the cycles. The E_{dtm} values during the unloading part of the fatigue loads became smaller during the initial period of the fatigue loading (Fig. 12 b, d, f), then remained constant, and finally decreased at high speed. Meanwhile, the E_{dsm} values during the loading and unloading parts of the fatigue loads exhibited the same change trend, i.e., quickly decreasing, remaining constant, and then accelerated decreasing as shown in Fig. 13. Furthermore, it was concluded that for the granite and marble specimens, the modulus decreased with an increase of the confining pressure and maximum load levels.

3.5 Fracture pattern

Failure patterns mainly refer to the fracture evolution of rocks under certain stress states and can be identified by the fracture fragments of the rocks during lab tests, the results of which can provide a clearer understanding on the rock failure process in engineering applications [2, 5]. In this study, the failure pattern of the granite, marble, and sandstone specimens in the uniaxial compression tests were all shear failures with a single failure plane as shown in Fig. 14a. The images of rock fragments after failure in uniaxial fatigue tests are shown in Fig. 14b. The failure pattern of the granite, sandstone, and marble subjected to fatigue loading was also shear failure, but there was a clear difference in the number of main failure planes. For the sandstone and marble specimens, the main fracture plane was a single shear fracture, but there were some tensile cracks surrounding the main fracture [2]. In addition, the granite specimens under fatigue loading had two main fracture planes presenting X shaped forms. During the loading process, there were two areas with X patterns and high shear stress concentrations. When the specimens experienced a stress higher than the damage stress level, some tensile microcracks developed but the growth was controlled by the shear stresses. In the UCS tests, because the rock was under high stress for a longer time than each cycle of fatigue loading, crack coalescence occurred in one of the two planes and normally rock failure occurred with a single failure plane. However, during the uniaxial fatigue tests, when crack coalescence was likely to occur at the high stress levels, the unloading process ceased it and therefore the cracks had the time and potential to gradually develop. Finally, both surfaces coalesced and generated a X failure type. For nearly all the rocks subjected to uniaxial fatigue loading, it was predicted that X type failure would occur. However, in most cases, the application of the confining pressure was a barrier for the development of the two failure surfaces. Besides the textural and mineralogical characteristics, the confining pressure and maximum loading stress level were prone to affect type of failure.

4 Conclusions

To perform a laboratory investigation on the failure properties of rocks coinciding with the field site, a series of special uniaxial fatigue tests were conducted using high static pre-stressed granite, marble, and sandstone specimens. The range of fatigue loads were between 70%-90% of the σ_{ucs}, 80%-90% of the σ_{ucs}, and 80%-95% of the σ_{ucs}. The fatigue life of the rock specimens under fatigue loads ranging from 70%-90% of the σ_{ucs} were larger than that of the specimens under fatigue loads ranging from 80%-90% of the σ_{ucs}. The result indicates that the static pre-stress has great influence on the fatigue failure of rocks. The fatigue life of the rock specimens under fatigue loads ranging from 80%-90% of the σ_{ucs} were larger than those of the specimens under fatigue loads ranging from 80%-95% of the σ_{ucs}, indicating that the maximum stress or amplitude level of fatigue loads also affected the fatigue life.

The lithology (mineral composition and textural properties) of the rock was the main factor affecting the occurrence of fatigue failures. Under fatigue loads ranging from 70%-90% of the σ_{ucs}, the granite and marble did not reach final failure after 4 hours of cyclic loading. Under fatigue loads ranging from 80%-90% of the σ_{ucs}, decreasing of the loading amplitude and the brittle behaviour of the granite led to granitic fatigue failures similar to the sandstone specimens, whereas the marble specimens did not fail. Metamorphism leads to the decrease and elimination of pores and other weakness planes and leads to the homogenous behaviour of the marble. Under fatigue loads ranging from 80%-95% of the σ_{ucs}, the sandstone had the longest fatigue life due to its high porosity and ductility.

The fatigue damage parameters related to the fatigue deformation, namely, the axial strain (ε_a), lateral strain (ε_l), volumetric strain (ε_v), dynamic tangent modulus (E_{dtm}), dynamic secant modulus (E_{dsm}) and the Poisson ratio (μ_d), all exhibited a three-stage change process. And the volumetric strain during the first cycle is a main factor affecting the fatigue life of the rocks. Furthermore, the dominant failure pattern of the granite, sandstone, and marble was shear failure, but there was a clear difference in the number of main failure planes for the rock specimens during the fatigue triaxial tests and the monotonic uniaxial compression tests.

Acknowledgments: This paper was supported by the National Natural Science Foundation of China (grant No. 51774326 and 11772357), as well as by the Open Fund of Mining Disaster Prevention and Control Ministry Key Laboratory at Shandong University of Science and Technology (grant No. MDPC201917).

Conflicts of Interest: The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Author Contribution Statement: Kun Du and Ming Tao provided the concept and wrote the draft of the manuscript. Rui Su, Jian Zhou, and Chengzhi Yang conducted the tests, the literature review and wrote the first draft of the manuscript. Kun Du, Ming Tao, and Aliakbar Momeni edited the draft of manuscript.

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