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Experimental investigations into the Mechanical Performance of Rocks under Fatigue Loads and Biaxial Confinements

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Abstract: In this research, a series of biaxial compression and biaxial fatigue tests were conducted to investigate the mechanical behaviors of marble and sandstone under biaxial confinements. Experimental results demonstrate that the biaxial compressive strength of rocks ~~in-under~~ biaxial compression ~~first~~ increases firstly, and ~~then subsequently~~ subsequently decreases—with the increase of the intermediate principal stress. The fatigue failure characteristics of the rocks in biaxial fatigue tests ~~is are a functions~~ of the peak value of fatigue loads, the intermediate principal stress and the rock lithology. With the increase of the peak values of fatigue loads, the fatigue life-lives of rock-specimens decreases. The intermediate principal stress strengthens the resistance ability of rocks to fatigue loads except considering the strength increasing under biaxial confinements. The fatigue lives of rocks increase with the increase of the intermediate principal stress under the same ratio of the fatigue load and their biaxial compressive strength. From the acoustic emission (AE) and fragments studies ~~showed that; it was found that~~ the sandstone has higher ability to resist the fatigue loads compared to the marble-, and ~~It was also found that~~ the marble generated a greater number of smaller fragments after fatigue failure compared to the sandstone. ~~From the study So,~~ it can be inferred that ~~fatigue load can enhance~~ the rock breaking efficiency, ~~and can induce~~ and rock burst ~~severely is higher or severer in-induced by fatigue loading~~ rocks under fatigue loading than that ~~in-induced by~~ monotonous quasi-static loading, especially for hard rocks.

Key words: Biaxial ~~confinements~~compression test; Fatigue loading; Acoustic Emission; Fragments; The ~~Intermediate~~ principal stress

1 Introduction

The underground ~~engineering~~ excavation changes the initial stress field of rocks in the vicinity to a secondary stress field [1-3]. The rocks located at the range of the secondary stress field is defined as “Engineering Surrounding Rock (ESR)”. The most affected part of the ESR by underground excavation is termed as “Excavation Damaged Zone (EDZ)”, which is closest to the underground ~~engineering~~excavation boundaries, as shown in Fig.1 a. The initial stress field is a

three-dimensional compressive stress condition ($\sigma_1 \geq \sigma_2 \geq \sigma_3 > 0$), while the secondary stress field is a biaxial stress condition ($\sigma_3=0$) or a uniaxial stress condition ($\sigma_2 = \sigma_3=0$) [4-6]. In general, ~~So, most EDZ rocks are subjected to a biaxial stress condition.~~ It is supposed that the stress path experienced by ~~most~~ EDZ rocks during ~~the~~ underground ~~engineering~~ excavations is referred to unloading of σ_3 to zero, with keeping σ_2 unchanged, and increasing σ_1 to a specific value [7], where σ_1 , σ_2 , and σ_3 are the maximum, intermediate, and minimum principal stress, respectively [8]. ~~So, most EDZ rocks are subjected to a biaxial geo-stress condition. In general, i~~It is found that σ_1 increases by 1.5-4.8 times to its initial value after the excavation through field testing [9].

Failure characteristics of EDZ rocks can reflect the stability of underground engineering structures. The stress conditions of EDZ rocks is a key factor affecting their failure characteristics and mechanism, which ~~are-is~~ coupled biaxial static stress and dynamic stress. The static stresses (σ_1 , σ_2 and σ_3) are mainly formed from tectonic or gravitational forces, and the detailed initial magnitudes of σ_1 , σ_2 , and σ_3 in several underground hard rock engineering structures located in China ~~is-are~~ summarized by Yang [10] as shown in Fig.1 b-d. The initial values of σ_1 , σ_2 , and σ_3 increase with the buried depth of underground engineering structures. The stresses σ_1 , σ_2 , and σ_3 increases at a rate of 42.8 MPa/km, 25.3 MPa/km, and 16.3 MPa/km, respectively. So, the deep buried EDZ rocks are subjected to ~~higher~~ in-situ static stresses. The dynamic stresses are induced mostly by earthquake, rock burst, drilling, blasting, or ore dropping in great quantity, and so on, which are repetitive cyclic disturbance with frequencies of 1-5 Hz [11-14].

The failure characteristics and mechanism of rocks under coupled static and dynamic stresses are studied mostly using split Hopkinson pressure bars (SHPB) and fatigue testing machines at a laboratorial scale [15, 16]. The difference between the two kinds of testing apparatuses is that the SHPB can apply dynamic impact loads with medium high strain rates ranging from 10 s^{-1} to 10^3 s^{-1} , and the fatigue testing machine can apply dynamic fatigue loads with frequencies of 0-20 Hz [15, 16]. In conclusion, the dynamic loads generated by fatigue testing machines are more consistent with the field dynamic loads [11-16]. Fatigue test is an important testing method to understand the failure characteristics of rocks under coupled dynamic (σ_F) and static stresses (σ_S). The fatigue failure is caused due to long-term repetitive loads with a peak stress level ($\sigma_{\max}$) lower than their static strength (σ_{ss}) [17, 18], as shown in Fig.2. A clear understanding of the time-dependent fatigue mechanical performance of EDZ rocks is significant for support design and potential hazard prevention in underground engineering [16-18].

Up to now, most previous fatigue tests were conducted on rock specimens under uniaxial compressive or conventional triaxial compressive stress state [19-21], as shown in Fig.2 a-b. According to the previous research studies, the key factors affecting rock fatigue behaviours are fatigue loading parameters, e.g. wave form (w_f), frequency (f), amplitude (σ_a), mean stress (σ_{mean}), valley stress ($\sigma_{\min}$), and peak stress ($\sigma_{\max}$), besides rock lithology and confining stress ~~confinements~~ (σ_3). The w_f used for repetitive loads in fatigue tests include sinusoidal waves, triangular waves, and square waves [22, 23], as shown in Fig.2c. The most frequently used f of fatigue loads in lab tests was in the range of 0.1 – 10 Hz, in accordance with the frequency of dynamic loads generated during earthquakes, rock bursts, and blasting, etc. [13, 14]. In fatigue tests, the σ_a and $\sigma_{\max}$ are varied for different rock specimens, and the relationships $\sigma_{\text{mean}} = (\sigma_{\max} + \sigma_{\min}) / 2$ and $\sigma_a = (\sigma_{\max} - \sigma_{\min}) / 2$ are applicable for fatigue loading. The studies conducted in uniaxial fatigue or conventional triaxial fatigue tests show that the strain increment caused by the sinusoidal loading waveform is larger than

that induced by the triangle loading waveform. It is caused due to the fact that the input energy by sinusoidal loading was larger than that by triangle loading [14, 19]. With the increase of σ_a and $\sigma_{\max}$, the rocks are easier to get final fatigue failure [24]. The fatigue resistance ability of rocks increased with the increase of f or the levels of confining stress ~~confinements in conventional triaxial fatigue tests~~ [25, 26].

Fig.1 Stress types and values subjected by EDZ rocks: (a) stress types in an underground mine, and (b-d) the maximum, intermediate, and minimum principal stresses vs buried depth of hard rock underground engineering in China, respectively

In summary, the stress condition of EDZ rocks is coupled biaxial static stress and dynamic stress. It is meaningful for stability analysis of underground engineering to study the failure mechanism and properties of rocks under the coupled static-dynamic stress state. Although Number number of studies have been conducted by different researchers on rock fatigue behaviours, but the biaxial compressive stress state of rocks in EDZ range was ignored in all the fatigue studies of rocks. So, in this research, a series of biaxial fatigue tests (BFT) have been conducted on marble and sandstone specimens to study the fatigue characteristics of rocks under biaxial confinements.

Fig.2 Stress state and stress path of fatigue tests in previous studies: (a) uniaxial confinement, (b) conventional triaxial confinement, and (c) stress path and wave parameters

2 Experimental methodology

2.1 Rock specimen preparation

The marble and sandstone cubical specimens with a side length of 50 mm were prepared and tested in this study, as shown in Fig.3 a. The mineral composition analysis through a light microscope using thin sections of rocks was conducted before the lab testing in this study. From the mineral composition analysis, it was found that the marble was composed of (35-45%) magnesite, (40-50%) calcite, and (5-25%) others (Fig.3 b), whereas the sandstone was composed of (50-70%) quartz, (10-30%) feldspar, and a little of muscovite and biotite (Fig.3 c).

Fig.3 Rocks used in this study: (a) specimens and their size; (b-c) mineral components of marble and sandstone, respectively

2.2 Testing system and loading procedure

Biaxial fatigue tests (BFT) were conducted using the TRW-3000 true-triaxial testing apparatus at Central South University, China. The maximum load capacity of the apparatus is over 2000 kN. The apparatus can be used to apply load along three mutually perpendicular directions (defined as X, Y, and Z, respectively) through different hydraulically driven pistons. The details of this apparatus can be referred to various published literatures [4, 5, 27, 28]. In this study, the cubic rock specimens of marble and sandstone specimens were placed between the Y and Z directions plane, as shown in Fig.4 a-b. Two LVDTs were used to monitor the axial and lateral deformation of specimens (Fig.5). Prior to the testing, the Vaseline and polythene sheets were applied evenly to the four surfaces of each the specimens to minimize the frictional resistance of the solid loading platens.

The biaxial confinements and stress path of BFT is shown in Fig.4 c-d. The stress along the Z direction of the true-triaxial testing apparatus is σ_1 , whereas the stress along the Y direction is σ_2 . The loading procedures are summarized as follows:

- (a) First, σ_1 and σ_2 were applied to the predefined values of σ_2 at a loading rate of 0.2 MPa/s;
- (b) Then, σ_1 was monotonically increased at a rate of 0.2 MPa/s to the predefined values of σ_1 , and the valley value σ_{min} of fatigue loads equals to the predefined values of σ_1 . The predefined values of σ_1 were the biaxial compression strength (σ_{bcs}) multiplying predefined ratios;
- (c) Finally, a sinusoidal fatigue stress load with peak stress σ_{max} of (90% or 95%) σ_{bcs} and f of 5Hz were applied on the specimens. The σ_{min} and σ_{max} were the biaxial compression strength (σ_{bcs}) multiplying certain predefined ratios, as listed in the Table 1. The σ_{min} equals to the predefined values of σ_1 . The predefined testing parameters are listed in Table 1.

The predefined testing parameters are listed in Table 1. In addition, several specimens in each of the rock types were tested in biaxial compression tests (BCT) to determine the σ_{bcs} of rock specimens under at different σ_2 values. In BCT, σ_1 was monotonically increased until the rock specimen failed after the σ_1 and σ_2 applied to the predefined values predefined value of σ_2 . The peak value of σ_1 in BCT was found to be σ_{bcs} .

Fig.4 TRW-3000 true-triaxial testing apparatus and testing procedure: (a) overall view, and (b) details for biaxial compression setup, (c) biaxial confinements of rock specimens, and (d) stress path in biaxial fatigue tests

Fig.5 Measuring methods of strain during biaxial compression loading

3 Experimental results and discussion

3.1 Biaxial compressive strength

The biaxial compressive strength (σ_{bcs}) of the cubical marble and sandstone specimens were determined and shown in Table.1. The σ_{bcs} of both the rocks were increased with the increase of σ_2 initially, and subsequently decreased with the increase of σ_2 . An exponent strength criterion for the rocks in biaxial compression tests was put forward in this study, as per the Equation (1). The exponential equation fits appropriately with the strength results of the rock specimens under different σ_2 , as shown in Fig.56.

$$\sigma_{bcs} = \sigma_{ucs} + A\sigma_{ucs}\sigma_2\exp(1 - B\sigma_2) \quad (1)$$

Where A and B are the material constants.

Fig.5-6 Biaxial compressive strength and fitting curves of marble and sandstone

Table 1 Predefined testing parameters and average biaxial compression strength in this study

Rock type	Testing type	Specimen <u>group</u>	σ_2	<u>Predefined</u> σ_1	$\sigma_{\max}$ <u>**</u>	σ_{bcs}
		No. <u>*</u>	(MPa)	<u>**</u> (%)	(%)	(MPa)
Marble	BCT	M-0-S	0	-	-	47.67
		M-10-S	10	-	-	64.67
		M-20-S	20	-	-	69.00
		M-40-S	40	-	-	59.60
	BFT	M-0-F	0	50	95	-
		M-10-F	10	50	95	-
		M-20-F	20	50	95	-
Sandstone	BCT	S-0-S	0	-	-	30.00
		S-10-S	10	-	-	45.33
		S-20-S	20	-	-	38.33
		S-0-F1	0	50	90	-
	BFT	S-0-F595	0	50	95	-
		S-10-F1	10	50	90	-
		S-10-F790	10	70	90	-
		S-20-F1	20	50	90	-
		S-20-F890	20	80	90	-

* Each specimen group contains 3 specimens, and the σ_{bcs} results shown in the Table are the average values under each of the σ_2 . **The predefined σ_1 equals to the $\sigma_{\min}$ of the fatigue loads, and σ_1 and $\sigma_{\max}$ were applied to the ratio of σ_{bcs} under different σ_2 in BFT.

3.2 Fatigue failure properties

The detailed biaxial fatigue test (BFT) testing parameters and results of both the rock types are listed-presented in Table 2. In the study, the effective fatigue loading time was quite shorter and the fatigue lives (FL) of all specimens were lower than those in other uniaxial or conventional triaxial fatigue testing results presented in earlier published literatures, which was due to that the $\sigma_{\max}$ of

fatigue loads was set at a high level in this study. From the study results, several conclusions on different aspects are summarized as follows:

Table 2 Fatigue testing parameters and results

Rock type	Specimen <u>group</u> No.	σ_2 (MPa)	σ_1 (MPa)	$\sigma_{\max}$ (MPa)	Time (s)	FL
Marble	M-0-F	0	23.84	45.29	11	55
	M-10-F	10	32.34	61.44	16	81
	M-20-F	40	34.50	65.55	21	104
Sandstone	S-0-F1	0	15.00	27.00	40	198
	S-0-F595	0	15.00	28.50	20	98
	S-10-F1	10	22.67	40.80	44	222
	S-10-F790	10	31.73	40.80	45	223
	S-20-F1	20	19.17	34.50	122	355
	S-20-F890	20	30.66	34.50	71	612

3.2.1 Fatigue life

Fatigue life (FL) is an important index to evaluate the resistance ability to fatigue loads of rocks, which is the applied cyclic number of fatigue loading until rock final failure. The larger the FL, the stronger the resistance ability of rocks is. The main conclusions in biaxial fatigue tests are as follows:

(1) The FL of specimen S-0-F1 (198) is greater than that of specimen S-0-F595 (98), which indicates that the FL decreases with the increase of $\sigma_{\max}$ under the same $\sigma_{\min}$ and σ_2 . The FL of specimen S-20-F1 (355) being smaller than the FL of specimen S-20-F790 (612) indicates that the FL increase with the increase of $\sigma_{\min}$ under the same $\sigma_{\max}$ and σ_2 . In conclusion, the change trend of FL in BFT tests is similar to that in uniaxial or conventional triaxial fatigue tests under the same confinements [20, 21];

(2) The FL of the specimens M-0-F, M-10-F, and M-20-F are 55, 81, and 104, respectively, and the FL of specimens S-0-F1, S-10-F1, and S-20-F1 are 198, 222, and 355, respectively, which shows a similar trend for each of rock types that the FL increase with the increase of σ_2 . In the fatigue testing on the rock specimens, the σ_2 can enhances the resistance capability to fatigue loads of rocks when the static strength increase phenomenon under biaxial confinements is considered, which can be called “the intermedium principal stress effect” in BFT.

(3) The FL of specimen M-0-F and S-0-595 are 55 and 98, respectively. The fatigue loads and stress confinements for the both specimens are similar, and the FL of sandstone is larger than the FL of marble. So, it can be concluded that the soft and plastic rocks have higher ability to resist the fatigue loading.

3.2.2 Stress-strain curve

Fig.6-7 Stress-strain curves in biaxial compression and fatigue tests: (a-c) marble, and (d- i) sandstone

The stress- strain curves of the marble and sandstone specimens in biaxial compression and fatigue tests are shown in Fig.6.7. The ε_1 is the strain along the σ_1 direction, whereas the ε_2 is the strain along the σ_2 direction. From the study, the key conclusions can be drawn as follows:

(1) Under the sinusoidal fatigue loading, the strain in hysteresis loop changes initially from greater to smaller and after few cyclic loadings, from smaller to greater. This trend is there until up to the specimen failure. While the strain hysteresis loop of the first cycle is always largest under triangle fatigue loading [14];

(2) The ultimate ε_1 and ε_2 values in BFT tests are greater than the strain values at the peak strength in BCT under the same σ_2 . The fatigue strain also equals to the post failure strain on the complete static stress-strain curve corresponding to the $\sigma_{\max}$ according to the previous studies [26];

(3) With the increasing of σ_2 , the ultimate ε_1 at the point of rock failure also increases. As shown in Fig.6-7 a-c, the ultimate ε_1 values for M-0-F, M-10-F, and M-20-F are approximately 0.53, 1.02, and 1.12, respectively, whereas the final ε_1 values for S-0-F1, S-10-F1, and S-20-F1 are close to 0.76, 1.08, and 1.38, respectively (Fig.6-7 d, f, h).

3.2.3 Failure fragment

The main fracture plane angles of the marble specimen were vertical, whereas the sandstone specimen showed several inclined fracture planes. So, from the fracture pattern, it can be concluded that the failure pattern of the marble specimen under biaxial confinements was due to tension, while the failure pattern of the sandstone specimen was due to shearing, as shown in Fig.78.

Fig.7.8 Failure patterns of rock specimens in BCT: (a-b) marble, and (c-d) sandstone

Fig.8.9 Failure fragments and their size distribution

Based on the rock fragment size, the rock fragments in BCT and BFT are divided into four categories, i.e. $>20\text{mm}$, $12\text{--}20\text{mm}$, $3\text{--}12\text{mm}$, and $<3\text{mm}$ (Fig.8.9). The weight of fragments in each of the categories are weighed as shown in Fig.9.10. The weight of the marble fragments in each of the categories increased or decreased monotonously with the increase of σ_2 . While the weight of the sandstone fragments showed a “V” shaped change trend with the increase of σ_2 , and the turning point was that under the $\sigma_2 = 10\text{MPa}$. For the marble, the weight of fragments with size of $>20\text{mm}$ in BFT was lighter than that in BCT, and the weight of fragments with size of $<20\text{mm}$ in BFT was heavier than that in BCT. The fragment results of marble demonstrate that when the fatigue dynamic failure of hard rocks occurs, higher number of smaller rock pieces are formed, and the energy utilization rate is higher than that in static compressive failure. So, it can be inferred that the higher the smaller rock pieces formation, the easier the rock piece ejection and rock burst occurrence [4, 29–30]. For the sandstone, the weight of fragments in each of the categories are similar in BFT and BCT. So, it can be concluded that the soft and plastic rocks have higher ability to resist the fatigue loading.

Fig.9-10 Weight of fragments with different sizes: (a-d) marble, and (e-h) sandstone

3.3 Acoustic Emission study characteristics

Two acoustic emission (AE) sensors were attached at the front and rear free surfaces of each of the specimens during testing, and the similar AE signals were received by both the sensors. So, only one sensor's data has been used in the following analysis. The AE hit rate, AE count rate and b -value for each of the specimens during loading process were calculated and shown in Fig.10-11 and Fig.11-12.

The AE hit rate, and the AE count rate mean the cumulative magnitude of the AE hit and the AE count in a minute during testing for each of the specimens, respectively, and the b -value reflects the relationship between the frequency and magnitude of earthquakes proposed firstly by Gutenberg and Richter in 1944 [31-33], as per the Equation (2). In case of the AE study, the Equation (2) can be modified as the Equation (3) using the AE parameters [32]. Moreover, the b -value represents the percentage of low amplitude AE hits in comparison to the high amplitude AE hits, which means that a large b -value indicates a larger proportion of low amplitude AE hits. In this study, b -value can be divided into two categories, which are the dynamic b -value and the overall b -value. The dynamic b -value is calculated using the AE data in 5-30 s before the specimen loaded to a certain axial stress or loading time, and the overall b -value is calculated using all the AE data of a specimen during testing. The main conclusions based on AE data analysis are as follows:

$$\lg N = a - bM \quad (2)$$

$$\lg N(A/20) = a - b(A/20) \quad (3)$$

Where M is the magnitude of earthquakes, N is the cumulative number of earthquakes with a magnitude of M , A is the amplitude of the AE hits, and N is the cumulative number of AE hits with an amplitude of A , a and b are empirical constants.

Fig. 10-11 AE hit rate, AE count rate and b value of rock specimens in BCT biaxial compression tests: (a-c) marble, and (d-f) sandstone

(1) The value of AE hit rate is approximately ten to one-tenth of that of the AE count rate for all the specimens, and both of them show a similar change trend for a-the same specimens. In BCT, the larger the σ_2 is, the longer the period of AE hit rate and AE count rate maintaining at a higher level. Besides, when the σ_2 is larger, multiple peaks appear in the AE hit rate and AE count rate, which provides proofs for the multiple fracture planes of rocks under biaxial confinements. In BFT, the AE hit rate and AE count rate of most specimens appear the first peak on the point of

fatigue loads applied original. In both of the test types, AE hit rate and AE count rate reach their maximum values when the specimens get final failure;

Fig. 11-12 AE hit rate, AE count rate and b value of rock specimens in-BFT biaxial fatigue tests: (a-c) marble, and (d-i) sandstone

(2) In BCT, the overall b -value for marble and sandstone decrease with the increase of σ_2 , such as the overall b -value for the specimen S-0-S, S-10-S, and S-20-S, are 2.136, 1.698, and 1.402, respectively, which indicates that the proportion of low amplitude AE hits decrease with the increase of σ_2 , and the size and inducing-energy of cracks producing AE signals is more larger for specimens under higher σ_2 . The overall b -value in BFT is lower than that in BCT except marble specimens under σ_2 of 0 and 10MPa, which indicates that fatigue loads can fracture rocks slowly, and the small

size crack dominate the fatigue of rocks, which is in concert with the distribution of failure fragments, especially for marble;

(3) The last dynamic b -value is equals to the overall b -value for all specimens, and start to decrease in 30-100 s before rock failure. If the rocks are under a stable condition, e.g. the axial stress being at a low level, the AE data is few, and the dynamic b -value is very small. When rocks are under a crack stable development state, the dynamic b -value maintains at a high level. When rocks are under a crack unstable development state, the dynamic b -value starts to decrease until to the overall b -value. So, the dynamic b -value can be used to predict the failure of rock specimens in BCT and BFT, as shown in Figs.110-112.

4 Conclusions

The fatigue failure behaviors of rocks, i.e. marble and sandstone, ~~rocks~~ under biaxial stress conditions were firstly examined using a True-triaxial loading testing apparatus. It is more meaningful for engineering practice that the study methods used in this paper are promoted and applied to the jointed rocks or rocks under different water or temperature conditions [34, 35]. The following-main conclusions in this study are summarized as follows:

(1) The biaxial compressive strength (σ_{bcs}) in biaxial compression test shows a change trend as “firstly increasing, and then subsequently decreasing with the increase of the intermediate principal stress σ_2 ”, which is consistent with that in true triaxial compression tests [5];

(2) There is a clear σ_2 effect on the fatigue failure of rocks in biaxial fatigue tests, even after considering the σ_2 effect on the σ_{bcs} , which a novel finding- in rock mechanics. So, the σ_2 enhances the resistance capability to fatigue loads of rocks;

(3) For ~~harder~~ rocks as marble in this study, the severe failure, such as rock burst, can be induced by fatigue loads easier than that induced by quasi-static loads. For ~~softer~~ rocks as sandstone in this study, the fatigue failure is similar to the compressive failure, and the soft rocks have higher ability to resist to the fatigue loading than hard rocks;

(4) Before the point of rock failure, the value of AE hit rate, AE count rate and the dynamic b -value decrease. So, these parameters from AE data can be used to predict the failure of rock ~~specimens~~ in BCT-biaxial compression tests and BFTbiaxial fatigue tests.

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