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Volumetric deformation and damage evolution of Tibet interbedded skarn under multistage constant-amplitude-cyclic loading

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Abstract: Multistage constant-amplitude-cyclic (MCAC) loading experiments were conducted on Tibet interbedded skarn to investigate and characterize fatigue mechanical behavior of the tested rock. Rock volumetric deformation, stiffness change, and fatigue damage evolution were analyzed along with the macroscopic failure morphology. The experimental results demonstrated that the volumetric deformation of the tested skarn was influenced by the interbed structure. Rock damage presented a two-stage pattern. The rock damage increased quickly at the beginning and subsequently became steady for long periods of time within a cyclic loading stage. A new damage evolution model was proposed on the basis of axial strain. Macroscopic failure morphology analysis revealed different fracture mechanisms, combining a tension-splitting mode, shear-sliding, and mixed shear-tension. In this study, the understanding of the anisotropic mechanical properties of interbedded skarn was highlighted, and this could contribute to the ability to predict the stabilities of rock engineering structures.

Keywords: Interbedded skarn; Anisotropy; MCAC loads; Volumetric deformation; Damage evolution

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1. Introduction

In civil and mining engineering works, rock fatigue is frequently encountered in many geotechnical engineering projects exposed to cyclic loads, such as earthquakes, blast vibrations in deep mines, and loading due to truck movements. Fatigue damage is a failure mode that cannot be ignored for rock engineering, during which many hazards occur due to cyclic or fatigue loads, such as rock bursts, mining landslides, and premature goaf collapses [1-4]. As such, investigation and characterization of fatigue damage behavior of rock masses is important for ensuring the long-term durability and safety of rock engineering structures.

Regarding rock fatigue damage, significant attention has been paid to maximum stress [5], stress amplitudes [6-7], dynamic frequency [8], loading waveforms [9-10], and strain rates [11]. Several fatigue models were proposed according to ultrasonic velocity [12], rock deformation [13-14], elastic modulus [15], energy dissipation [16-17], acoustic emission characteristics [18], and the load-unload response ratio (LURR) [19]. For most experiments, constant amplitude during the entire fatigue loading tests was used, whereas the mean load of the applied load was constant. Furthermore, the applied upper stress was used to determine the fatigue lifetime of the rock. This fatigue testing included low-cycle and high-cycle constant amplitude tests. The low-cycle tests were primarily used to reveal the rock fatigue behavior because the rock could fail after limited numbers of cyclic loading [20]. High-cycle constant amplitude tests were extensively employed to obtain the fatigue limitation of rocks [21-22]. It was proved that the amplitude cyclic loading path variation is closer to the actual stress disturbance circumstances. For example, in deep mining, frequent blasting could be viewed as cyclic loading, through which multi-level effects are applied on specific rock structures. In open-pit mining, the applied stress amplitude on open-pit slopes was not constant because the amplitude cyclic stress conditions increase in rock cumulative damage change the rock structure. In a hydropower station, the rise and drop of the water level of periodic loading is a multistage process, during which the rock will eventually be fractured because of the multistage cyclic loading. For roads and railways, the periodic load is multi-level because of the increase and decrease of the load capacity in parallel to the density of the vehicles on the road. For example, Zhang et al. [23] carried out multi-level frequency cyclic loading tests on coal, for which the energy dissipation, hysteresis, and micro-seismicity characteristics were identified. Peng et al. [24] revealed the loading frequency on sandstone strength and deformation under triaxial cyclic loading conditions, for which the influence of loading frequency on irreversible deformation was investigated. Yang et al. [25] conducted triaxial testing on granite and sandstone in a multi-level cyclic way, and the influences of two typical loading paths on the evolution pattern of the damping coefficient, damping ratio, and elastic modulus under different confined conditions were investigated. Zhou et al. [26] conducted numerical tests on rock material that was exposed to multi-level cyclic loads, and the effects of the loading path on both strengthening and fracture were revealed. Wang et al. [27] conducted testing on granite samples in a multi-level cyclic loading way, and the influences of the previous freeze-thaw cycle on the mechanical properties and acoustic emission pattern were revealed. According to the fatigue strain for rock that was exposed to multi-level cyclic loads, Wang et al. [28] proposed a damage evolution model, in which a two-phase damage evolution pattern was studied. Because rock fracture is an energy-driven process, Gao et al. [29] conducted multi-level triaxial cyclic testing on jointed and intact rock masses, for which the stress state on the process of rock progressive failure was examined. Wang et al. [30] investigated the energy dissipation characteristics of rock under cyclic loading and found that the energy conversion pattern is strongly impacted by rock structure. Vaneghi et al. [31] carried out multistage uniaxial cyclic compression loading experiments; the deformation and damage response of sandstone (soft rock) and granodiorite (hard rock) and the stress-strain hysteresis loops of soft rock showed three stages, whereas there were two stages for hard rock.

In nature, most rocks exhibit anisotropy and heterogeneity, and there are many geological discontinuities and layers that have considerable tensile or shear strength [32]. However, the aforementioned cyclic and fatigue loading experiments were mostly conducted on intact rocks. In this work, the cyclic mechanical behavior of anisotropic rocks under multi-stage cyclic loading was revealed. In addition, in all studies to date, the increasing-amplitude cyclic loading test, rock damage, and fracture characteristics exposed to multistage constant-amplitude-cyclic (MCAC) loads have been studied but not in depth. Therefore, the aim of this research is to study the effects of rock structure (e.g., interbed structure orientation) on rock deformation and damage evolution under MCAC loads. Rock samples with interbedding orientation angles of 0°, 30°, 60°, and 90° with respect to the coring direction were used to perform the MCAC experiments. This study focuses on the effects of interbed structure on the deformation and damage evolution characteristics of skarn. The study results will help to improve the understanding of the damage and fracture behaviors within interbedded and anisotropic rocks under complex loads.

An introduction section that includes a literature review has been included in the first section. In section 2, experimental methodology is explained, particularly with respect to the multi-level cyclic loading path and testing procedure. In section 3, the rock volumetric deformation, fatigue damage evolution, and macroscopic failure pattern are analyzed.

2. Experimental methods and procedures

2.1. Rock sample preparation

The tested rock was collected from the Jiama mine in Tibet, China. The lithology of the rock is gray skarn. The Jiama mining area belongs to the jurisdiction of Jiama township and Sibu township of Mozhugongka county of Lhasa city. The geographic coordinates are east longitude 91°43 '06 "−91°50' 00" and northern latitude 37 ° 29 '49 "- 29 ° 43' 53". The climate in the mining region is a typical continental climate. The rainy season is wet and cold, and the winter is cold and dry; there is a large temperature difference between day and night. The annual rainfall is about 500 mm, and most of the rainfall is from June to September. The frost-snow season is July to August. The minimum temperature in winter can reach 40 degrees below zero, and the maximum temperature in summer can reach 38℃. The sampling site is an open pit slope, and the elevation is 4970 m (Fig.1). After observation of the fresh rock section, which is produced through blasting excavation, the skarn presented as an interbedded structure, and black limestone interlayers could be observed; in addition, the skarn was characterized by pyrite bands and natural fractures.

The interbed structure can also be observed from the BSE-SEM (Electron backscattered diffraction- Scanning electron microscope) image shown in Fig. 2. This demonstrates that the structure within the tested rock samples is homogenous; specifically, the rock matrix was grey, interbed bands were cyan black, and pyrite grains were white. The rock matrix is fine crystal with a low degree of cementation. The particle size is 0.5-2 mm, and the matrix content is about 70%. The interlayer part has a fine vein-like structure with high mineral grain cementation and relatively dense and high stiffness. The particle size is 0.2-0.5 mm, and the content is about 30%. The matrix is relatively unconsolidated and has a small density; the matrix tends to generate strain localization, and thus, it is easy to produce axial deformation in the process of uniaxial compression. The XRD (X-Ray Powder Diffraction) results presented in Fig.3 reveal that the mineral composition of the skarn samples was composed of quartz (63.4%), biotite (8.9%), anorthite (9.9%), and calcium (18.8%); the black interlayer was mainly composed of quartz (15%), muscovite (80%), pytite (1%), and polylithionite (1%). Using the method suggested by the International Society for Rock Mechanics and Rock Engineering (ISRM), the diameter of the rock samples was determined to be 50 mm, and the length was determined to be 100 mm.

2.2. Experimental apparatus and scheme

For the interbedded skarn samples, MCAC loading testing was conducted with a rock mechanics testing apparatus (GCTS RTR 2000). During the entire deformation process, a pair of LVDT (Linear Variable Differential Transformer) devices were installed at the longitudinal parts of rock sample to measure axial deformation, and an LVDT was installed at the middle part of rock to obtain lateral deformation. A dynamic loading frequency of 0~10 Hz could be achieved with the testing machine. A series of mechanical parameters (such as axial strain, lateral strain, loading, stress, damping ratio, elastic modulus, and Poisson's ratio) could be recorded throughout the entire deformation. Before fatigue loading, a static loading condition with a constant displacement rate of 0.06 mm/min (such as 1.0×10^{-5} s^{-1}) was employed, and the axial stress reached 10 MPa. Subsequently, a dynamic loading frequency of 0.5 Hz (signifying that the achieved loading and unloading cycle was within 2 s) was applied to the test skarn, and the loading path was controlled by sinusoidal stress. The stress control method was adopted through cyclic loading with a specified stress amplitude of 10 MPa applied to the samples with 0°, 30°, 60°, and 90° interbedding orientation.

2.3. Damage evolution based on axial deformation

During fatigue deformation, the skarn axial strain was measured with a pair of LVDT devices. According to studies related to rock fatigue mechanical properties, the axial strain is a good parameter for describing damage evolution compared to the lateral strain. Because the lateral strain of the middle part of the sample was measured, local deformation characteristics of the rock were produced. As a result, the cyclic axial strain was employed in this work to characterize the accumulation of rock damage at each loading cycle. According to previous studies [33-34], the stress, strain, and elastic modulus during fatigue deformation can be expressed as follows:

$$\frac{\sigma}{E} = \frac{\varepsilon_\mathrm{d}\varepsilon_0}{\varepsilon_\mathrm{d} - \varepsilon_0} \tag{1}$$

where σ, ε, and E are respectively the stress, strain, and elastic modulus of the tested rock before cyclic loading; ε_0 is the initial axial strain before mechanical testing, and ε_d is the final axial strain at the moment of sample failure.

The damage index, *D*, could be obtained as follows:

$$D = \frac{\varepsilon_\mathrm{d}}{\varepsilon}\frac{\varepsilon - \varepsilon_0}{\varepsilon_\mathrm{d} - \varepsilon_0} \tag{2}$$

According to Eq. (2), the characteristics of damage evolution during fatigue loading were obtained. The final strain, ε_d, was determined as the strain value when the specimen failed at the peak stress value.

3. Experimental results

3.1. Cyclic stress-strain characteristics

For typical skarn samples with various interbedding orientations, the complete stress-strain curves are presented in Fig.4, and the fatigue mechanical parameters are summarized and presented in Table 1. There is a clear pattern showing that the stress-strain curves and the associated fatigue mechanical behaviors were impacted by the rock structure. At first, fatigue peak stress presented a decrease and subsequently increased with an increase in interbedding orientation; the stress was a minimum for a sample having an interbedding orientation of 30°. The fatigue loading stage and fatigue lifetime were also affected by the interbedding orientation. The fatigue loading stages were 13, 3, 8, and 13 for samples with interbedding orientations of 0°, 30°, 60°, and 90°, respectively. The corresponding fatigue lifetime values were a maximum and minimum for a sample with interbedding orientations of 0° and 30°, respectively. Affected by the interbed structure, the deformation between the rock matrix and interlayer differed, and the capacity to resist deformation was structural-controlled. For the samples that contained one single fracture with a 30° dip angle, the failure stress is the smallest. The samples tended to break under this dip angle, which is supported by the theory of structural plane mechanics proposed by Jaeger et al. [35]. As presented in Fig. 4, a hysteresis loop formed because of irreversible plastic deformation. During the first several cyclic stages, the rock samples were under a compaction state, and the area of the hysteresis loop was relatively low; in addition, the sample shapes changed slightly. As the cyclic loading stages increased, the area of the stress hysteresis loop increased, and the corresponding shape changed significantly during the last several cyclic stages, indicating that there was relative large plastic deformation within the skarn samples. It is noteworthy that the hysteresis loop displayed a pattern that changes from sparse to dense at each loading stage except for the final failure stage. The sparse pattern was attributed to the large plastic deformation that was caused by the increase in axial stress; in contrast, after a few cycles, the rock structure was compacted again, and the hysteresis loop changed to a dense state. This result demonstrates that the rock fracture increased during the axial stress-increasing period, whereas the cumulative damage of rock was mainly influenced by the stress increase. For the samples with 0° and 30° interbedding orientations, rock failure occurred during the cyclic loading stage; however, rock failure occurred during the stress-increase stage. At the fatigue loading stage, the damage degree of the rock was less than that of the stress-increase stage.

3.2. Cyclic deformation characteristics

The hysteresis loop is due to irrevocable plastic deformation in rock samples. In this case, the deformation characteristics were studied to reveal the influence of interbedding orientation on rock damage evolution. The relationship between the maximum axial strain and cycle number during various cyclic stages is presented in Fig.5. The changes of axial strain were not apparent within a cyclic stage except for the ninth loading stage for the skarn with 0° interbedding orientation. However, axial strain increased, and the corresponding incremental rate became higher in different cyclic stages. The pattern of axial strain was impacted by the rock structure, whereas the incremental rate was the highest for the sample with 30° interbedding orientation.

The relationship between the maximum lateral strain and the cycle number is presented in Fig.6. The lateral strain was measured with a chain-typed LVDT, which was installed in the middle of the rock samples. Lateral deformation was not apparent during the first few cyclic loading stages and changed abruptly after several cyclic loading stages. Lateral strain increased quickly at the 9th, 2nd, 3rd, and 6th cycles, whereas the incremental rate was affected by the interbedding orientation. For the sample with 0° interbedding orientation, before the 9th cyclic stage, the change in the lateral strain was relatively low; however, once high lateral deformation occurred, the corresponding rate increase became higher. For the sample with 30° interbedding orientation, sliding deformation was prone to occur at the interface of the rock matrix and corresponding interlayers, for which the lateral deformation was controlled by shear-sliding. For skarn samples with 60° and 90° interbedding orientations, lateral deformation increased slowly during each cyclic loading stage.

Once the axial and lateral strains were obtained, rock volumetric strain could be calculated using $\varepsilon_v=\varepsilon_a+2\varepsilon_l$. The volumetric strain was the overall reflection of rock deformation. Fig.7 shows that the rock volume changed from compression to expansion at the 8th, 2nd, and 3rd stages for skarn for corresponding orientation angles of 0°, 30°, and 60°, respectively. However, for skarn with 90° interbedding orientation, the rock volume was in a compression state during the entire loading process. The reason for this is that the uneven deformation of the rock interbedded structure results in large axial deformation, which results in the constant compression of rock volume deformation. The change in the volumetric strain reflected well the structural-control characteristics of rock fatigue deformation.

3.3. Changes of rock elastic parameters

Irreversible rock deformation is also an expression of rock stiffness reduction. Fig.8 presents the relationships among secant modulus (E_s), Poisson's ratio (ν), and cycle number. It was demonstrated that E_s presents a decreasing trend, with a decreased rate of acceleration, especially near the rock failure stage. In addition, E_s decreased within a cyclic level. The decrease in E_s indicates the degradation of rock stiffness, and the cyclic loads resulted in accumulated damage within rock samples. The results presented in Fig.8 also indicate that E_s was impacted by the orientation of interbedding structures; its value was the highest for the sample with 0° interbedding orientation and the minimum for the sample with 30° interbedding orientation. From the evolution of Poisson's ratio with cycle number (Fig.8e-h), ν increased with cycle number, and it increased faster as the cycle number increased. A fast increase in Poisson's ratio indicates an abrupt increase in lateral deformation of the rock, possibly resulting in an increase of volumetric deformation. For rock with 30°

interbedding orientation, the change in ν was higher than in the other cases. This result indicates that the shear-sliding among the rock matrix and interbeds was the most severe during the fatigue loading process.

3.4. Damage evolution analysis

According to Eq. (1), the damage evolution of rock during the fatigue loading process was plotted and is presented in Fig.9. The changes in the damage factor with cycle number demonstrate the accumulated damage of the tested skarn samples. Among the multiple cyclic stages, the accumulated damage was large during the first few stages, and the corresponding incremental rate of decrease was analogous to the increase in cyclic stages. Because of the increase in axial stress at the adjacent two cyclic loading levels, large irreversible deformation appeared at the beginning of each cyclic loading stage and then tended to be stable. That is, in each cyclic loading stage, the damage evolution increased rapidly at first and then remained stable for a long time. Within a fatigue loading stage, high damage occurred because of the increase in the axial stress level, and a certain amount of microcracks formed during this time frame. However, the previous microcracks were subsequently compacted in a cyclic loading stage. At the last cyclic loading stage, it was observed that damage accelerated until sample failure occurred.

To predict the damage evolution of interbedded skarn during the entire loading process, the accumulated damage at the end of each cyclic loading stage can be expressed as a function of the relative cycle (n/N_f), as presented in Fig.10. A model of fatigue strain, which is used to describe damage evolution, is presented in Eq. (3) and has been proven to be the same as that in the studies of Wang et al. (2021). The form of the proposed function is expressed as:

$$D = 1 - \left(1 - \left(n / N_f\right)^a\right)^b \tag{3}$$

where D is the damage variable defined by the dissipated energy; n and N_f are the cycle number and fatigue lifetime, respectively; a and b are the material-dependent parameters. The fitting results obtained using Eq. (3) are listed in Table 2 and demonstrate that there is a high correlation between D and the relative cycle (n/N_f); in addition, the fitting results presented in Table 2 indicate that the anisotropic damage pattern was affected by the interbed structure. The fitting curve morphologies differed for rocks of different interbedding orientations. For skarn samples with 0°, 60°, and 90° orientations, rock damage first increased quickly and then became slow at high relative cycles; however, for the sample with 30° interbedding orientation, damage first increased slowly and then increased with an accelerating rate until rock failure occurred. It was demonstrated that the proposed damage evolution model could be used to express these two types of trends with high correlation, further proving the reliability of the proposed damage evolution model.

3.5. Failure morphology analysis

The aforementioned analysis demonstrated that rock damage and deformation characteristics were strongly impacted by the corresponding internal structure. Macroscopic failure morphology of rock was the external expression of the corresponding internal damage evolution. The failure morphology and crack sketch pictures are presented in Fig.11. Different failure modes can be observed from the macroscopic failure pattern, and the failure pattern was influenced by the interbed structure. Although the tested rock samples have strong anisotropy and heterogeneous characteristics, a certain amount of natural fractures can be found from the rock surface, for which the interbed structure was controlled through a failure mode. For the sample with 0° interbedding orientation, the scale of the crack network was the highest, and a high amount of cracks that were parallel to the loading directions were stimulated, corresponding to a typical tension-splitting failure mode; for the sample with a 30° interbedding orientation, the crack scale was a minimum and shear-sliding occurred during rock deformation; for the sample with a 60° interbedding orientation, it was demonstrated that a mix of shearing and the tension failure mode occurred for this sample, and a portion of the cracks propagated along the interbeds; for the sample with a 30° interbedding orientation, the two apparent cracks formed from the rock top to bottom, and the width of these two cracks was larger than for the other two cases. In addition, these two cracks should be the stimulants of the pre-existing natural fractures, and the tension failure mode was observed for this sample. The macroscopic failure morphology description further proved the fact that rock failure was the corresponding structural dependence.

4. Discussion

Considering the complicated stress disturbance effect on engineering rock mass, the applied cyclic load differed from the conventional constant amplitude loads; specifically, it was a type of multi-level constant-amplitude load. This signifies that although the stress amplitude was constant, the cyclic loading was applied at various stages with a stress-increase pattern. This loading mode was much more suitable for rock in open pit mining. With rock mass excavation from the top down for an open-pit mine, the geostatic stress that acted on rock mass increased as the excavation depth increased. At each excavation level, because of the disturbance of blast variations and tramcar loads, the actual stress disturbance that acted on rock was multi-level instead of single-level during the entire loading process. Therefore, fatigue mechanical properties of interbedded skarn were investigated under MCAC loads. The influences of interbed structure on rock strength, volumetric deformation, elastic characteristics, and damage evolution were analyzed. The testing results demonstrated that rock axial strain, lateral strain, volumetric strain, strength, lifetime, secant modulus, Poisson's ratio, and damage accumulation were impacted by interbed structure.

What is different from the previous constant amplitude loading with one loading level is that the damage at each cyclic stage presented a two-stage trend. Rock damage first presents a quick increase and then achieves a stable level. This damage evolution pattern is similar to that of rock that is exposed to amplitude-increasing cyclic loads. At the start of each cyclic loading stage, the sudden increase in axial stress led to relatively large damage to the rock. After cyclic loads, damage to the rock was not severe compared to the stress-increasing moment. The damage evolution of rock exposed to MCAC loading was revealed by a nonlinear power function, and it was found that the model could well characterize damage accumulation. It is noteworthy that the shape of the damage model curve was impacted by the interbed structure. For rock with 30° interbedding orientation, the damage propagation mode differed from that of the other cases. This first demonstrates a slow pattern and then a fast pattern, indicating that once shear-sliding occurred, damage displayed an accelerating growth pattern.

In this study, a dynamic loading frequency of 0.5 Hz was utilized, and the stress-increasing range was 10 MPa. This is a kind of low-frequency disturbed stress, and the loading condition corresponds to the far-field blast vibration. In a further study, complicated stress disturbance with a variable loading frequency and a stress increment will be performed. Moreover, the Jiama mining region is a typical high-altitude and cold region, and repeated freeze-thaw cycles occur during mining. The influences of the freeze-thaw treatment on the mechanical behavior of rock fatigue should be investigated. Previous studies have indicated that deterioration of rock structures is strongly impacted by freeze-thaw cycles [36-39]; for the interbedded skarn that was studied in this work, the previous freeze-thaw damage accumulation on the internal structure of rock may degrade its fatigue life when it is subjected to MCAC loading conditions. Thus, the combination of freeze-thaw cycles and disturbed loads should be considered simultaneously for Tibet skarn.

5. Conclusions

MCAC loading experiments were carried out on Tibet interbedded skarn to investigate the anisotropic fatigue mechanical responses. The strength and deformation characteristics and the damage evolution were investigated. According to the above analysis, the following conclusions are obtained:

The volumetric deformation of the tested anisotropic skarn was influenced by the interbed structures. The transition stage from rock volume compression to expansion was different; in addition, the rock volume was always under a compressive state for the sample with 90° interbedding orientation. The rock secant modulus, which indicates the stiffness and weakness characteristics, decreased as the cyclic stage increased, whereas the increase in Poisson's ratio was rapid until rock failure.

Rock damage displayed a two-stage pattern: damage first increased quickly and then was steady for a long time within a cyclic stage. A new damage evolution model was proposed on the basis of rock axial strain, and the damage accumulation curves displayed various patterns, which were influenced by the interbed structure.

Macroscopic failure morphology analysis revealed different fracture mechanisms and was influenced by rock structure. Failure of rock began as the tension-splitting mode and transformed to shear-sliding and to mixed shear-tension for the tested skarn samples. The differences in the rock failure morphology were the external expression of the rock damage evolution.

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Data Availability Statement

All of the data, models, and code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest statement

No conflict of interest exists in the submission of this manuscript. The manuscript was approved for publication by all of the authors. We would like to declare that the described work was original research that has not been previously published.

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Figure captions:

Fig.1 Rock sampling site.

Fig.2 Interbedded structure detection in a skarn sample from a BSE-SEM image.

Fig.3 XRD results for mineral composition identification.

Fig.4 Axial and lateral stress-strain curves for samples with interbedding orientation angles of 0°, 30°, 60°, and 90°.

Fig.5 Maximum axial strain evolution with cycle numbers during cyclic loading stages for skarn samples with different interbedding orientations.

Fig.6 Maximum lateral strain evolution with cycle numbers during cyclic loading stages for skarn samples with different interbedding orientations.

Fig.7 Maximum volumetric strain versus cycle numbers in various cyclic loading stages.

Fig.8 Rock stiffness changes during the fatigue loading process for skarn samples with interbedding orientation angles of 0°, 30°, 60°, and 90°.

Fig.9 Damage evolution of skarn samples with cyclic loading number.

Fig.10 Predictive model between the accumulated damage variable and relative cycle for skarn samples.

Fig.11 Failure morphology of interbedded skarn samples with different orientation angles.

Table captions:

Table 1 Summary of skarn fatigue mechanical parameters of different rock structures.

Table 2 Fitting parameters of damage evolution model for tested skarn samples.