DYNAMIC SHEAR FAILURE OF FREEZE-THAWED TIBET HORNFELS SUBJECTED TO MULTILEVEL CYCLIC SHEAR (MLCS) LOADS: INSIGHTS INTO STRUCTURAL DEPENDENT FAILURE CHARACTERISTICS

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Shear instability behavior is typical failure mode of rock mass in civil and mining engineering. Many attempts have been performed for rock joints or nonpersistent rock bridge under static shear conditions, yet the shear failure of rock mass subjected to cyclic or fatigue shear conditions is not well understood. Multilevel cyclic shear (MLCS) loading experiments were carried out on freeze-thawed hornfels to reveal the fracture and energy evolution characteristics using a self-special designed rock dynamic shear testing apparatus. The effect of the preexisting natural fracture on rock shear strength, deformation, energy dissipation, and shear failure pattern were experimentally investigated. The testing results show that aperture of open-mode fractures increases quickly, and this kind of natural fracture contributed a lot to rock failure. The evolution of stress hysteresis loop and its pattern are impacted by natural fracture, and it determines the damage accumulation. In addition, a damage evolution model was proposed to describe the damage evolution defined by the dissipated energy; the model can well describe the two-stage damage propagation for each cyclic stage and the entire cyclic loading process. Good agreement was found among the irreversible strain, energy dissipation, and failure morphology that are influenced by the preexisting natural fractures. It is suggested that the rock dynamic shear failure behaviors are rock structural dependent; the disturbed stress alters the energy dissipation and release characteristics.

1. Introduction

Deformation and damage resulting from shearing usually occur during the construction and development of rock structures [1–3]. The sliding or fracturing of rock mass under shear stress would lead to different kinds of engineering disasters, such as landslides, rock collapse, spalling, and shear-type rock burst [2]. Rock failure related to shearing fracturing is usually dynamic and not static; shear fracturing of rock is usually caused by disturbed stress, such as blasting vibration, earthquake, and excavation. As a result, it is necessary to investigate the dynamic shear instability behavior of rock in order to improve the understanding of shear failure mechanism and guide the design of rock constructions.

Many previous works studied the shear failure of rock mass by laboratory or in situ direct shear tests [4–6]. Accurate determination of rock shear strength by laboratory direct shear test on small scaled specimens is the premise of comprehensive understanding of large scale in situ behaviors of rock mass, which has been studied by many scholars [7, 8]. Laboratory direct shear tests are concentrated in two kinds of works: one kind is for rock joints [9–11], and the other kind is for rock bridge (i.e., nonpersistent joints in rock mass) [12–14]. It is accepted that the shear instability behavior of rock mass is impacted by the normal stress, roughness of rock joints, joint persistence, etc. [13, 14]. Numerical investigations have made great attempts on shear strength and failure pattern of rock joints and rock bridge...
from different perspectives. Currently, many kinds of direct shear apparatus have been developed by improving the normal control, such as the constant normal load (CNL) shear devices and the constant normal stiffness (CNS) device. In addition, direct shear devices considering three-dimensional stress conditions have also been designed by Feng et al. [15]; the influence of lateral stress on rock shear fracturing was fully considered.

However, it is worth noting that in the past, almost all the studies are for rock shear instability behavior under static shear stress paths [10–14]. However, for rock engineering rock mass, it is very common that the loading acting on rock is cyclic in essence. For example, in disturbed stress of blasting, excavation, and drilling in rock mass of open pit slope, the shear instability of rock mass is strongly impacted the disturbed stress [16]. In addition, rock mass from a tunnel or cavern may undergo deep fracturing caused by stress disturbance during construction operation [17]. This is to say, the dynamic shear failure of engineering rock mass is closed to the real stress state in civil and mining engineering. Plenty of previous studies have been performed to reveal the rock mechanical behaviors under stress disturbance. Generally, the disturbed stress is equivalent to cyclic or fatigue loading [18–20]. After a detailed literature review, it is obvious that almost all the studies on rock cyclic or fatigue mechanics are concentrated on compressive cyclic loads (i.e., uniaxial or triaxial loading path) [21–23]. Nevertheless, no study seems to have investigated cyclic or fatigue shear mechanical behaviors of rock joints or rock bridge. So it remains mostly unknown what the fracturing characteristics of rock mass exposed to cyclic shear stress and how the shear failure morphology would depend on cyclic loading conditions.

To fill this knowledge gap, a rock dynamic shear testing apparatus characterized with varied-frequency and varied-amplitude performance was developed. Using this apparatus, this work characterizes and analyzes the shear fracturing evolution of hornfels rock containing natural fractures. The effect of natural fracture on fracture and energy evolution was investigated. A thorough comparison of fatigue strength, deformation, energy conversion, and failure pattern was revealed by dynamic shear testing. In addition, a fatigue damage evolution model defined using the dissipated energy was proposed to describe the two-stage damage evolution of hornfels.

2. Methodology

2.1. Test Material and Sample Preparation. The rock lithology of the studied rock is hornfels that obtained from a Tibet Jiaoyan open pit slope in a cold region western of China. The Jiaoyan open pit mine belongs to the Jiama copper polymetallic mine, as shown in Figure 1. The surrounding rock of the ore deposit presents as a kind of mosaic or block structure, the rock quality designation (RQD) value is about 49.38%, and its saturated uniaxial compressive strength is 99.95 MPa. The longitudinal wave velocity of the dry and saturated rock mass is 5225 m/s and 5534 m/s, respectively. From outcrop investigation, the rock mass develops 3–4 joint groups commonly, and the average spacing of them is 0.53 m; the joints are mostly closed with argillaceous and pyrite filling. The altitude of the Jiaoyan open pit slope is 4700 m~5300 m, and the minimum temperature is -40°C below zero in winter. In addition, the frequent mining blast variation, mechanical excavation, and tramcar dynamic loads aggravate the shear instability of rock mass. As a result, the stability of the open pit slope is obvious impacted by coupled freeze-thaw and stress disturbance.

To reveal the mesoscopic structure of hornfels, scanning electron microscope (SEM) and X-ray powder diffraction (XRD) analysis were carried out on rock before freeze-thaw treatment. As shown in Figure 2(a), a multihole mesostructure was developed within rock; in addition, several microcracks can also be observed. It is suggested that the water-ice phase transformation occurs within the holes and microcracks and the freeze-thaw treatment has a strong effect on rock mechanical properties. The XRD analysis reveals the mineral composition in Figure 2(b); it is shown that main minerals contains quartz, anorthite, biotite, and calcium manganese, and their content is 48.2%, 9.5%, and 16.8%, respectively. In order to perform a dynamic shear test, all the tested rock samples were prepared as a cubic shape with the size of 100 mm × 100 mm × 100 mm according to the recommended method by ISRM. Six sides of the rock sample were polished to ensure that the parallelism, and the nonuniformity error is less than 0.1 mm and 0.05 mm, respectively.

In this work, eight hornfels samples divided into two groups with different preexisting natural fracture volume were used to carry out the shear testing, as shown in Figures 3(a)–3(d). For each tested rock, three types of natural fractures including closing-mode natural fracture (CF), opening-mode (OF), and pyrite filling-mode (FF) all can be detected from rock surface. The total volume of those natural fractures was roughly calculated as their aperture multiplied by their area. The fracture aperture is measured by an electron microscope, and the natural fracture area is determined by sketch its profile with the help of SOLIDWORKS software. Figures 3(e)–3(h) present the shape of the opening-mode, closed-mode, and filling-mode natural fractures. The filled-mode fracture is filled with pyrite; strong contact between the pyrite and rock matrix is found. Statistical result of the natural fracture volume for typical tested rock is listed in Table 1.

2.2. Testing Apparatus. The dynamic shear testing system RDST-1000 was developed to conduct the cyclic shear tests. This system can apply variable frequency and variable amplitude cyclic loads on rock samples. The applications of the normal and shear stresses are both servo-controlled, and the maximum normal and shear stresses are 1000 kN and 1000 kN, respectively. The horizontal shear stress can be performed in sine, square, and triangular patterns, and the maximum frequency can reach 10 Hz. The environmental box can realize the lowest temperature of -40°C. The acoustic emission data can be obtained during the testing process to characterize the rock fracturing process; the designed system is shown in Figure 4. This testing system has three innovation features, as follows:
(1) The dynamic loading, servo control, and complex stress paths under variable frequency and load amplitude can be realized. During open pit mining, the external disturbance acting on rocks has a moderate strain rate and a wide range of stress amplitudes. For this system, the cyclic shear process is realized by two dynamic servo valves to independently control the normal and shear oil cylinder. This testing system can fulfill the precise servo control and large loads.

(2) The cooling problem of large flow hydraulic power source is solved. The cyclic load requires the use of high-pressure pumps with large flow rates. The high-pressure pump will generate a lot of heat during its operation. Therefore, the hydraulic oil is heated rapidly. If the temperature is too high, the compressibility of the hydraulic oil will be undermined. High temperature will also lead to thermal expansion of the pipeline, and the tightness of the system will be seriously affected.

Figure 1: Rock sampling site from the Jiaoyan open pit slope in the Jiama copper polymetallic mine. (a) The Jiaoyan open pit mine; (b) rock blocky structure description of a slope step; (c) rock sample size for cyclic shear testing.

Figure 2: Description of the mesoscopic structure of hornfels. (a) Typical SEM picture to observe the pores and microcracks; (b) XRD result to identify mineral composition.
Figure 3: Typical rock samples with different initial natural fracture volume. (a–d) Rock sample with natural fracture volume of 0.76%, 0.68%, 3.17%, and 2.53%, respectively, for dynamic shear testing.

Table 1: Statistical analysis of the natural fracture volume within the marble samples.

| Sample ID | Total natural fracture volume ratio $R_V$ (%) | Opening-mode fractures and sealed with calcite $R_{VO}$ (%) | Closing-mode fracture with quartz vein $R_{VC}$ (%) | Filling-mode fracture with pyrite bands $R_{VP}$ (%) | Testing conditions |
|-----------|-------------------------------------------|-------------------------------------------------|------------------------------------------|-------------------------------------------------|-------------------|
| HS-1      | 0.68                                      | 0.31                                            | 0.32                                      | 0.05                                            | Static shear testing, normal stress 5 MPa, 0.08 mm/min |
| HS-2      | 2.87                                      | 1.19                                            | 0.77                                      | 0.91                                            | Cyclic shear testing, normal stress 5 MPa, dynamic frequency 0.5 Hz, 30 cycles each stages |
| HS-3      | 3.44                                      | 2.69                                            | 0.52                                      | 0.23                                            |                                                               |
| HS-4      | 2.66                                      | 1.62                                            | 0.58                                      | 0.46                                            |                                                               |
| H1        | 0.73                                      | 0.26                                            | 0.32                                      | 0.15                                            |                                                               |
| H2        | 2.68                                      | 1.21                                            | 0.64                                      | 0.83                                            |                                                               |
| H3        | 3.17                                      | 1.92                                            | 0.82                                      | 0.43                                            |                                                               |
| H4        | 2.35                                      | 1.38                                            | 0.58                                      | 0.39                                            |                                                               |

Figure 4: Design drawing of the dynamic shear testing machine.
The high-accuracy measurement of rock deformation under cyclic load is realized. For previous tests, the strain gages, extensometers, or chain-type strain measuring devices are often used to measure specimen deformation. For high-frequency cyclic stress, the deformation of rock sample is very slight and swift, and the highly precise measurement is difficult to realize. The grating extension meter can solve this problem. During rock shear testing, two grating sensors were used to measure the shear deformation and two grating sensors were employed to measure the normal deformation.

To investigate the dynamic shear failure characteristics of freeze-thawed hornfels samples, the experimental apparatus herein includes a vacuum saturation apparatus, an ultralow temperature freezer, an FLIR industrial camera with its pixel size of 6 μm, and a special developed dynamic shear rock mechanical apparatus of RDST-1000, as described in Figure 5.

### Figure 5: The experimental apparatus in this work.

- **(a)** The ultralow temperature freezer;
- **(b)** the vacuum saturation device;
- **(c)** the freeze-thaw scheme;
- **(d)** the FLIR industrial camera;
- **(e)** principle of the dynamic shear apparatus;
- **(f)** TDW 1000 rock dynamic shear testing machine.

#### 2.3. Testing Procedures.

The hornfels obtained from the Jiaoyan open pit slope was carried out firstly freeze-thaw treatment and then multilevel cyclic shear loading; the detailed testing procedures are described as follows:

1. For the prepared hornfels samples, first, the rock vacuum saturation treatment in a vacuum saturation apparatus (Figure 5(a)) was carried out for 24 hours; the purpose of this step is to determine the rock pores to be filled with water.
2. After vacuum saturation, the samples were carried out freeze-thaw cycles in an ultralow temperature environmental box (Figure 5(b)). The determination of the maximum freezing temperature and duration refers to the actual temperature of the open pit slope. The freeze-thaw treatment was performed in an ultralow temperature freezer, and the freeze-thaw scheme is shown in Figure 5(c); the rock sample experienced an 8-hour freezing treatment and an 8-hour thawing treatment. Repeated freeze-thaw cycle was performed, and a maximum of 60 freeze-thaw cycles was conducted.
3. After freeze-thaw treatment, the hornfels samples were used to conduct static shear testing and increasing-amplitude cyclic shear testing. Before applying shear stress on rock samples, the normal stress is set to be 5 MPa in advance. For the static shear testing, a horizontal loading rate of 0.08 mm/min was applied on the samples until failure of rock. A cyclic loading controlled by sinusoidal wave with its frequency of 0.5 Hz was applied on the hornfels samples. The dynamic loading frequency was determined from situ disturbed stress monitoring using a blast vibration monitoring device. This dynamic frequency reflects the influences of far-field blasting seismic wave and the moving frequency of tramcars. That is to say, the time duration of 2 s can realize the shear loading and unloading in a cycle. In each subsequent cyclic shear loading stage, the stress amplitude was increased by 3 MPa until the sample...
failure. For each cyclic shear loading stage, 30 cycles were applied to the rock samples.

During shear deformation, a side of the hornfels sample was exposed in the air in order to take pictures by a FLIR industrial camera (Figure 5(d)); the sampling rate is 80 frames per second.

3. Result Analysis

3.1. Changes of Natural Fracture Aperture. For rock exposed to freeze-thaw conditions, the cement strength between the natural fractures and the rock matrix would decrease owing to the stimulation of pyrite bands and generally exhibited as the aperture change. After repeated freeze-thaw cycles, the natural fracture aperture on rock surface was measured by an electron microscope. The changes of natural fracture aperture against freeze-thaw cycle are shown in Figure 6(a). It is shown that the aperture of the opening-mode fractures (OF), closed-type natural fracture (CF), and pyrite filled natural fracture (FF) all increases with increasing freeze-thaw cycles. The increasing trend of them is different; it is shown that the aperture incremental of OF is the largest and the incremental degree of FF is the smallest. This result indicates that the water-ice phase transformation is series within the opening-mode natural fracture, and the existing of the opening-mode fractures impacts a lot to rock shear capacity. The frost heaving force within the opening-mode fractures is the largest than the other cases, and the structural deterioration of those kinds of rock is the most obvious. The changes of natural fracture volume ratio are presented in Figure 6(b). It is shown that the sample HS-3 has relatively high OF and CF volume ratio.

3.2. Typical Static Shear Stress Strain Responses. In this work, the static shear stress strain responses are shown in Figure 7(a). It is shown that the peak strength of the hornfels decreases for the tested samples of HS-1, HS-2, HS-3, and HS-4. The peak strength does not show a positive correlation with the natural fracture volume. For the sample HS-3, its natural fracture volume is the maximum; however, its strength is larger than the sample HS-4. The result indicates that natural fracture pattern inside hornfels has a great influence on its shear mechanical properties. Along the shear direction, for the sample HS-3, structure combination of natural fracture and rock matrix blocks the shear deformation of the sample. The peak shear strain in Figure 7(b) is less than 0.5% displaying brittle fracture; in addition, the maximum shear strain presents a similar changing trend with the peak shear strength.

3.3. Representative Cyclic Shear Stress Strain Responses. A multilevel cyclic shear loading path was applied to the hornfels samples; the loading path and the associated shear stress strain curves are shown in Figures 8(a)–8(d). It is shown that cyclic loading stage is different for the tested hornfels samples, which is impacted by the rock structure. The cyclic loading stage is 10, 8, 8, and 4, respectively, for hornfels samples of H1, H2, H3, and H4. The fatigue lifetime for them is 286, 218, 212, and 106 cycles. Although under the same loading path, the stress strain response differs a lot. It is shown that the fluctuation of stress strain curves is relatively...
3.4. Cyclic Shear Deformation Characteristics. The relationship between the shear strain and elapsed time is shown in Figure 9. An overall similar trend can be observed that deformation grows faster and faster and especially nears to the failure stage. Owing to the interactions between the rock matrix and natural fractures along the shear direction, deformation curve fluctuates for the sample having high natural fracture volume (i.e., hornfels H3). At each cyclic shear stage before the failure stage, the shear strain grows quickly at the first few cycles and then gets to steady; however, shear strain has been growing all the time at the last few cyclic shear stages, and its growth rate becomes faster and faster until rock failure. The evolution of shear strain curves further indicates the influence of rock structure on rock cyclic shear responses.

As stated above, the formation of stress hysteresis loop indicates the occurrence of irreversible deformation inside rock samples. The relationship between the rock irreversible shear strain and cycle number is plotted in Figures 10(a)–10(d). The evolution pattern of the irreversible shear strain curve shows a two stage characteristics before the last loading stage; i.e., it grows fast and then gets to steady within a cyclic shear stage. However, it increases quickly at the last cyclic shear stage until rock failure. It can be also observed that the growth rate of irreversible shear strain becomes faster as loading stage increases, indicating the occurrence of relative large plastic deformation in the tested hornfels samples. Figures 10(e) and 10(f) plot the maximum shear strain against cyclic shear stage. The strain first increases and then increases with increasing natural fracture ratio for the tested samples; it is shown that the strain is the maximum and minimum for the sample H3 and H4, indicating the influence of opening-mode natural fracture on rock deformation.

3.5. Energy Conversion during Shear Deformation. Rock damage and fracture propagation are driven by energy. During the whole shear deformation, the total strain energy ($U$), elastic strain energy ($U_e$), and the dissipated energy ($U_d$) are calculated according to the studies of Wang et al. [24], Bories et al. [25], and Wang et al. [26, 27]. The strain energy of $U$, $U_e$, and $U_d$ can be calculated from the cyclic stress strain curves (Figure 11), as follows:

\[
U = \int_{\epsilon_1}^{\epsilon_{max}} \sigma d\epsilon = \frac{1}{2} \sum_{i=1}^{n} (\sigma_i + \sigma_{i+1})(\epsilon_{i+1} - \epsilon_i),
\]

\[
U_e = \int_{\epsilon_1}^{\epsilon_{max}} \sigma d\epsilon = \frac{1}{2} \sum_{i=1}^{n} (\sigma_i + \sigma_{i+1})(\epsilon_{i+1}^e - \epsilon_i^e),
\]

\[
U_d = U - U_e = \frac{1}{2} \sum_{i=1}^{n} (\sigma_i + \sigma_{i+1})(\epsilon_{i+1} - \epsilon_i).\]
Figure 8: Description of fatigue mechanical behaviors of the hornfels samples. (a-1 to d-1) Multilevel cyclic shear loading path for the tested rock; (a-2 to d-2) typical cyclic stress train curves for the tested rock samples; (e) comparison of fatigue strength and peak strain; f. Comparison of fatigue lifetime of the tested samples.
The calculation of the $U_d$, $U_e$, and $U_d$ for a loading cycle is illustrated in Figure 11(a). The total energy $U$ corresponds to the area of ABCD from the loading stress strain curve; elastic energy $U_e$ equals to the area of EFDC on the unloading curve; it is released during the unloading stage. $U_d$ can be obtained as the difference of the total energy $U$ and the elastic energy $U_e$. The generation of $U_d$ indicates the occurrence of damage owing to rock structure deterioration, such as hole spalling, crack initiation, propagation, and coalescence; $U_d$ is irreversible. For rock experience $N$ loading cycles, the obtained dissipated energy is presented in Figure 11(b).

Figure 12 depicts the evolution of strain energy and shear cycles. At the first loading stage, no damage occurs or the rock damage degree was less, the total input energy transfers to the elastic energy, and the total energy curve is overlapped with the elastic energy curve. With the increase of cyclic shear stages, the elastic energy curve deviates the total energy curve because of the damage propagation. At the same time, the dissipated energy grows gradually. The difference between the total and elastic energy curves becomes larger as cyclic shear stage increases. The occurrence of the dissipated energy is the result of damage accumulation; the dissipated energy is employed to drive the propagation of fractures. The dissipated energy curve grows quickly as shear cyclic stage increases indicating the formation of large-scale fractures at the shear surface. The fracture propagation becomes faster and faster.

To further reveal the influence of natural fracture on energy dissipation and release, Figures 13(a)–13(c) plot the $U$, $U_e$, and $U_d$ versus shear cycles. What is interesting is that sample H3 has the largest $U$, $U_e$, and $U_d$, indicating that sample H3 is difficult to be fractured under shear loading.
Figure 10: Rock irreversible shear strain for the tested hornfels samples. (a–d) Plots of the irreversible shear strain against cycle number of each cyclic loading stage; (e, f) plots of maximum shear strain and irreversible shear strain against loading stage.
path. Although the peak stress is not the largest among the tested samples, it has the largest shear strain. The formation of shear failure surface needs to consume the largest input energy; the fracture scale at the region of shear failure surface should be the largest. To quantitatively obtain the relationship between \( U_d \) and the cyclic shear stage, Figure 13(d) plots their relationship using equation fitting approach. A power equation that has the highest correlation coefficient is found; the correlation coefficient is 0.977, 0.968, 0.984, and 0.995 for H1, H2, H3, and H4, respectively. The fitting equations are expressed as follows:

3.6. Cyclic Damage Evolution Modeling. From the evolution pattern of \( U_d \) in Figure 13(c), it is shown that \( U_d \) presents a two-stage increasing trend; i.e., \( U_d \) increases quickly at the initial loading cycles, and then, it increases steady at the following cycles of each stage. The overall trend of \( U_d \) shows a first steady and then faster increasing trend indicating the unstable crack propagation with the increase of cyclic shear stage. An inverted “S” shape model has been proposed and is widely used to describe material fatigue damage [28]. However, for the tested naturally fractured hornfels herein, the growth trend of the damage accumulation curve indicates that they do not obey the inverted “S” model. Therefore, a new model is needed to be developed to describe the damage evolution characteristics. For the proposed model, it should meet the criterion that damage factor is 0 when cycle number is 0 and it is 1 when rock fails. As a result, a new damage evolution model based on dissipated energy is proposed and its form is expressed as

\[
D = 1 - (1 - (\epsilon_i^\sigma)^a)^b,
\]

where \( D \) is the damage factor defined by the dissipated energy, \( n \) is the number of loading cycle, \( N_i \) is the fatigue life, and \( a \) and \( b \) are fitting parameters related to the material properties. Figure 14 shows the fitting results; it is proved that the proposed model is suitable to reflect the two-stage damage evolution of hornfels. The parameters for the damage evolution model are summarized in Table 2.

3.7. Crack Propagation during Shear Deformation. During the multilevel cyclic shear deformation, an industrial camera was used to capture the cracking process of the tested hornfels sample as shown in Figure 15. In order to well capture the crack initiation, propagation, and coalescence, the rock surface was carried out speckle treatment. For the H1 sample, the initial natural fracture volume is the least and most of the natural fracture is closed-state; therefore, the preexisting natural fracture impacts a little to the shear failure surface. The shear failure surface is relatively smooth and straight. For the H2 sample, impacted by the preexisting natural fracture, the closed-mode fractures were stimulated and shear failure surface is relatively complicated. Seven cracks were stimulated at the failure stage. For the H3 sample, the shearing stress was almost perpendicular to the natural fractures, the rock matrix between the fractures serves as lock section, and the shear surface is difficult to be coalesced. During shear deformation, repeated opening and closing of a natural fracture of C1 can be observed. For the H4 sample, an inclined natural fracture exists into the hornfels sample; it was stimulated subjected to increasing-amplitude cyclic shear stress. From the failure morphology of hornfels samples, it is shown that shear failure of hornfels is impacted by rock structure; i.e., the preexisting natural fracture alters the initiation and propagation path of shear failure surface.

4. Discussions

Shear instability behaviors occasionally occur in rock mass, and direct shear tests are mostly used to reveal the strength
and fracturing characteristics of rock under various normal stress [9–12]. For rock mass in the civil and mining engineering, rock mass is actually exposed to the condition of stress disturbance. However, the conventional CNS or CNL direct shear tests only consider rock under static loading condition and are not suitable for investigating fracturing mechanism of rock under cyclic shear condition. In this work, a new rock dynamic shear testing machine was developed and hornfels samples obtained from an open pit slope were tested according to characterize the fracture and energy evolution characteristics.

Although plenty of previous studies have investigated shear failure of rock joints or intermittent jointed rock, the loading path is almost static condition; the hysteresis characteristics of rock subjected to cyclic shear loading and unloading is poorly understood. Nevertheless, the present work analyzes direct shear test data because the shear stress-strain responses under different normal stress are mostly available from direct tests. It would be debatable whether the fracture evolution and the associated shear failure mechanics of rock under dynamic shear paths are the same with the previous static loading paths. The results in this work reveal the fact that rock shear fracturing behaviors are strongly impacted by rock structure. What is different from the previous studies is that rock is tested under stress disturbance conditions. By selecting bedding structural rock with different initial natural fracture volume, it is confirmed that the existence of natural fracture alters the crack propagation path and the associated energy dissipation and release. The deformation and energy evolution are different.

Figure 12: Evolution of the total energy $U$, elastic energy $U_e$, and dissipated energy $U_d$ for the tested hornfels samples.
from the conventional monotonic shear test results. The irreversible plastic deformation during loading and unloading is the source resulting in the damage evolution characteristics. In this work, the applied normal stress and dynamic frequency are set to be 5 MPa and 0.5 Hz; a thorough comparison between cyclic shear fracturing characterized by dynamic shear test data is left as a topic of the future research.

5. Conclusions

A series of multilevel shear fatigue loading experiments were conducted on hornfels containing natural fractures to investigate the shear instability behaviors. The results of this study clearly show a significant effect of the preexisting natural fracture on fatigue fracture evolution and energy dissipation. The main conclusions are as follows:

![Figure 13](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.2113/2022/9551299/5521689/9551299.pdf)
The novel dynamic shear apparatus can be used for investigating the cyclic or fatigue shear fracturing behaviors of rock mass under complicated stress disturbance conditions. The testing results show that the apparatus has a good performance.

(a) The fatigue strength, deformation, energy conversion, and shear failure morphology are influenced by the preexisting natural fractures. The experimental results further indicate the structural controlling mechanism of rock subjected to cyclic shear paths.

(b) Table 2: Damage evolution model of naturally fractured hornfels under increasing-amplitude cyclic shear loads.

| Sample ID | Natural fracture volume $R_v$ (%) | $a$ | $b$ | $R^2$ |
|-----------|----------------------------------|-----|-----|-------|
| H1        | 0.73                             | 2.563 | 0.638 | 0.999 |
| H2        | 2.68                             | 1.271 | 0.395 | 0.993 |
| H3        | 3.17                             | 1.720 | 0.362 | 0.993 |
| H4        | 2.35                             | 2.029 | 0.578 | 0.999 |

Figure 14: Damage evolution model for the hornfels samples expressed by dissipated energy. (a–d) The hornfels sample with initial natural fracture volume of 0.76%, 2.68%, 3.17%, and 2.35%, respectively.
The evolution of stress hysteresis loop and its pattern determines the damage accumulation.

(3) A new damage evolution model was defined using the dissipate energy. It is found that the damage model can well describe the two-stage damage propagation for each cyclic stage and the whole cyclic loading process.

(4) Rock dynamic shear failure and the associated energy evolution characteristics are impacted by the interaction between the preexisting natural fractures and rock matrix. Good agreement has been found among the irreversible strain, energy dissipation, and failure morphology that are influenced by rock structure.

**Data Availability**

The experimental data used to support the findings of this study are included within the article.

**Conflicts of Interest**

The authors declare no conflict of interest.

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