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Trans. Nonferrous Met. Soc. China 25(2015) 2708−2717
Transactions of Nonferrous Metals Society of China
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Mechanical behavior of red sandstone under cyclic point loading

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Received 24 September 2014; accepted 10 March 2015

Abstract: The mechanical properties of red sandstone subjected to cyclic point loading were investigated. Tests were conducted using MTS servohydraulic landmark test system, under cyclic loadings with constant amplitudes and increasing multi-level amplitudes. The frequencies range from 0.1 to 5 Hz and lower limit load ratios range from 0 to 0.60. Laboratory investigations were performed to find the effect of the frequency and the lower limit load ratio on the fatigue life and hysteresis properties of sandstone. The results show that the fatigue life of sandstone decreases first and then increases with the increase of frequency and lower limit load ratio. Under the same cycle number, the spacing between hysteresis loops increases with rising frequency and decreasing lower limit load ratio. The existence of “training” and “memory” effects in red sandstone under cyclic point loading was proved.

Key words: red sandstone; cyclic point loading; fatigue life; hysteresis loop; penetration; training effect; memory effect

1 Introduction

With more and more mineral exploitations going into deep underground, traditional mining with blasting method tends to trigger rock-burst frequently [1]. Researchers around the world are devoted to finding non-explosive mining method [2]. In the coal mines, various continuous mining machines have been invented and made the production process safer and more efficient. However, for the metal mines with very compact and hard rock mass, these machines are found not to be effective for severe abrasion [3]. Many major mining or machinery companies have invested heavily in developing new equipments. We also paid lots of effort in this field. Recently, our studies have revealed that appropriate combination of static and dynamic loads can increase the rock fragmentation efficiency greatly [4−6]. Based on the findings, we have improved the cantilever excavator by adding an impact device, which can apply low-frequency cyclic impacts behind the cutting head. During excavation, the conical cutting teeth contact the rock mass and apply forces. The loading mode of the cutting teeth can be treated as cyclic point loading, based on the fact that the contact area between the cutting teeth and rock face is very small and the applied force has certain frequencies and amplitudes.

To improve the working performance of excavator for hard rock mines, it is necessary to investigate the rock behavior under such loading conditions. Cyclic loading has been studied by many researchers. For example, GUO et al [7] conducted a systematic study on the fatigue damage and irreversible deformation of salt rock subjected to uniaxial cyclic loading. Their results showed that the fatigue life of rock was mainly determined by its structure, amplitude and upper stress. They also concluded a “three-stage law of axial deformation”. LIU et al [8,9] applied axially cyclic loading to sandstone samples to experimentally determine the effects of confining pressures on their dynamic residual deformation and dynamic mechanical properties, and found that when the confining pressure was larger, the sample failed after fewer cycles, while the axial strain and the number of cycles at failure increased with the increase of frequency. BAGDE and PETROŠ [10,11] studied the fatigue property of intact sandstone under different waveforms, amplitudes and frequencies. They concluded that all these three factors had great effect on its fatigue property, and the most critical damage condition was square wave, low frequency

Foundation item: Projects (51322403, 51274254) supported by the National Natural Science Foundation of China; Project (2015CB060200) supported by the National Basic Research Program of China
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DOI: 10.1016/S1003-6326(15)63895-X

and amplitude. TAO and MO et al [12] studied the behavior of rocks under cyclic loading, and found that the loading waveform and the cycle amplitude had important effects on the deformation. In each cycle, the deformation caused by the triangle waveform loading was smaller than that by the sine waveform loading. The fatigue life became shorter when the cycle amplitude was larger. ATTEWELL [13] reported that in cyclic compression tests, the fatigue life of rock increased with decreasing the stress amplitude. He found that, with decreasing the stress amplitude, the number of cycles to failure increased on a logarithmic scale. The results indicated that, the percentage of strain hardening increased with increasing the number of load cycles at a given maximum applied stress, cyclic frequency and stress amplitude. XIAO et al [14,15] revealed that the fatigue life decreased with the increase of the maximum stress, amplitude and fatigue initial damage.

The former researches mainly studied on cyclic tests where specimens were loaded with whole face contact, and few studies focused on rock specimens under cyclic loading with point contact. In this work, tests of rock under different cyclic point loadings were conducted. Some mechanical characteristics were presented, such as the effect of frequency and lower limit load on rock's fatigue life, which may bring insight for the coming invention of new mining machinery.

2 Laboratory testing schemes

Laboratory tests were performed on red sandstone specimens extracted from Yunnan Province of China. The rock was in good geometrical integrity and petrographic uniformity. Rock specimens were cut into cylindrical shape with a diameter of 50 mm and a length/diameter ratio of 0.8. All specimens were naturally dried and had average mass density of 2220 kg/m^3.

2.1 Equipment and loading cone

The MTS servohydraulic landmark test system was used for the tests. In order to apply cyclic point loading to the specimens, a special loading cone (Fig. 1) was installed on the clamping groove of the system. The cone was manufactured according to the suggested method for determining point load strength by ISRM (International Society for Rock Mechanics) [16].

2.2 Cyclic point loading tests

In this study, the following two kinds of cyclic point loading tests were arranged: 1) cyclic loading test with constant amplitude, and 2) increasing multi-level loading test. The former was mainly to study the effect of frequency and lower limit load on penetration (the reduced distance between two loading cones), cyclic modulus and the fatigue life of red sandstone. The latter was designed to find out if training or memory effects also exist in red sandstone under cyclic point loading.

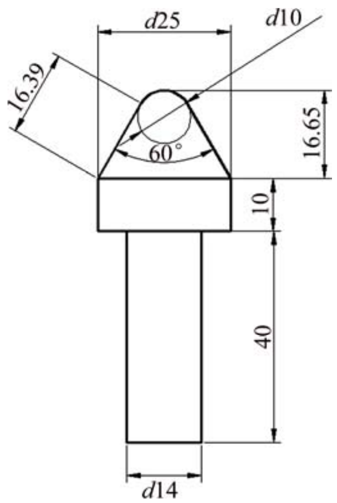

Fig. 1 Geometric parameters of loading cone (unit: mm)

2.2.1 Cyclic loading tests with constant amplitude

In the cyclic loading tests, rock specimens were firstly loaded with static force P_{min}, which was applied by force-controlled model with a speed of 9 kN/min. Then, the dynamic loading with specified frequency and upper limit load P_{max} was applied, as shown in Fig. 2.

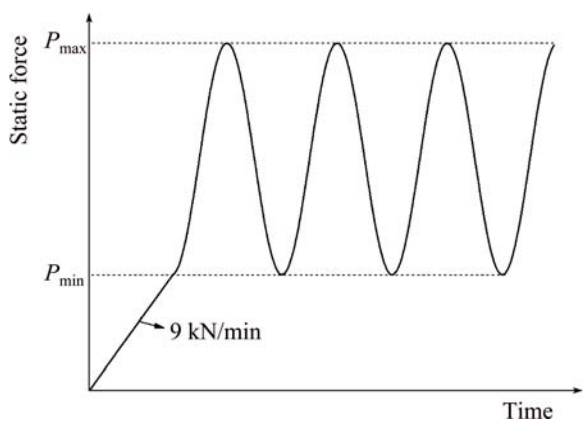

Fig. 2 Cyclic loading with constant amplitude

The dynamic loadings have a sinusoidal waveform. And the wave frequencies varied from 0.1 to 5.0 Hz, which were chosen according to the mining practice. The upper limit loads and lower limit loads were taken according to the average static point load strength of the specimen (P_a), as listed in Table 1. The static test was conducted with an axial displacement-controlled model, and the displacement rate was 1.3 mm/min.

The loading conditions and results of the constant amplitude cyclic point loading tests are given in Table 2, where the loading parameters R_{max} (upper limit load ratio) and R_{min} (lower limit load ratio) were expressed as

$$R_{max} = P_{max} / P_a \tag{1}$$

$$R_{min} = P_{min} / P_a \tag{2}$$

Table 1 Test results of specimens under static point loads

Sample	Peak strength, P/kN	Average peak strength, P_a/kN
J-1	4.454	
J-2	4.845	4.628
J-3	4.586	

Table 2 Loading conditions and test results of specimens under cyclic point loadings with constant amplitude

Sample	f/Hz	R_{max}	R_{min}	Fatigue life/s	Cycle number	Remark
D-11-1				690.4	68	No failure
D-11-2	0.1	0.94	0.3	700.5	69	No failure
D-11-3				705.1	69	No failure
D-5-1				310.1	60	
D-5-2	0.2	0.94	0.3	288.2	55	
D-5-3				305.3	59	
D-2-1				25.6	8	
D-2-2				28.3	9	
D-2-3	0.5	0.94	0.3	22.5	6	
D-2-4				25.6	7	
D-2-5				28.1	9	
D-3-1				255.1	244	
D-3-2				316.7	309	
D-3-3	1	0.94	0.3	300.4	290	
D-3-4				350.1	339	
D-3-5				319.1	308	
D-4-1				580	2846	No failure
D-4-2				403.1	1961	
D-4-3	5	0.94	0.3	559.1	2741	No failure
D-4-4				582.1	2856	No failure
D-4-5				570.1	2796	No failure
D-1-1				436.6	218	
D-1-2	0.5	0.94	0 (P_{min}=0)	420.3	205	
D-1-3				455.1	222	
D-6-1				75.6	32	
D-6-2				76.1	35	
D-6-3	0.5	0.94	0.25	500	245	No failure
D-6-4				81.2	35	
D-6-5				67.5	28	
D-7-1				16.9	3	
D-7-2				15.1	2	
D-7-3	0.5	0.94	0.35	17.2	3	
D-7-4				12.1	1	
D-7-5				25.2	7	
D-12-1				117.3	52	
D-12-2	0.5	0.94	0.5	126.1	58	
D-12-3				102.9	46	
D-13-1				700.2	341	No failure
D-13-2	0.5	0.94	0.6	710.8	350	No failure
D-13-3				750.6	370	No failure

2.2.2 Increasing multi-level loading tests

In the increasing multi-level loading tests, the loading waveform was also sinusoidal wave. The frequency was chosen to be 0.5 Hz. Five loading gradients were set as 0−1, 1−2, 2−3, 3−4 and 4−5 kN, respectively. In each loading gradient, 20 cycles were applied. Once one gradient was completed, the loading was transferred to the next gradient automatically. The loading profile can be seen in Fig. 3.

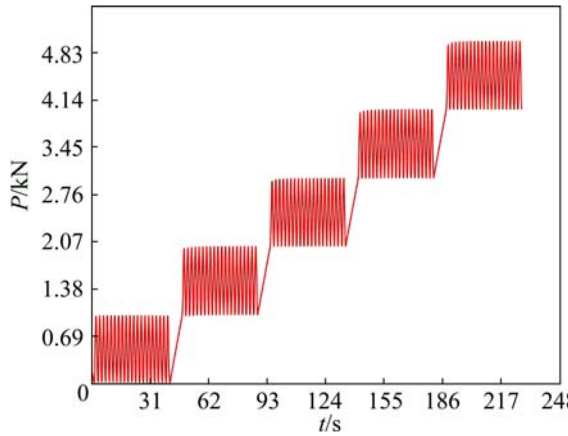

Fig. 3 Cyclic loading with multi-level steps at 0.5 Hz

In order to seat the specimen and ensure good alignment of the loading cones, a small pre-load was applied at the beginning of cyclic loading test. The pre-load was about 0.1 kN and was applied by force-controlled model with a speed of 9 kN/min.

The shapes of specimens that were broken in tests are almost the same as that of Sample J-3 (Fig. 4), which is broken in half along the axial direction.

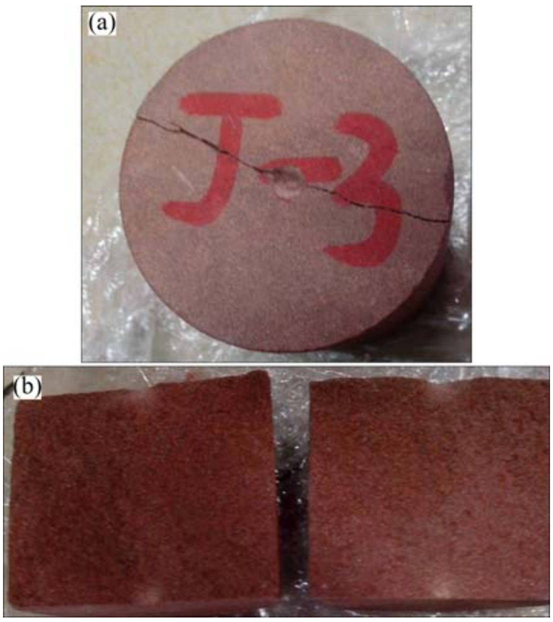

Fig. 4 Shape of Specimen J-3 after breakage: (a) Top view; (b) Cutaway view

3 Results

3.1 Fatigue life

3.1.1 Effect of frequency on fatigue life

Some typical P(axial load)−L(penetration) curves of specimens under different loading frequencies are presented in Fig. 5, from which we can see that the fatigue lives of specimens D-5-3 (0.2 Hz), D-2-1 (0.5 Hz) and D-3-2 (1 Hz) are 305.3, 25.6, and 365.7 s, respectively. Obviously, the fatigue life is affected by the frequency.

In order to find out the effect of the frequency on the fatigue life of the rock, more results of Table 2 are presented in Fig. 6. It is obvious that the fatigue life falls down first and then rises up with increasing the frequency. This means that the speed of rock-breaking increases first and then decreases. So, a very meaningful conclusion can be obtained: there exists a beneficial frequency under which the rock breaks much more easily. For the rock type studied in this work, the beneficial frequency locates in the vicinity of 0.5 Hz.

As the upper limit load and lower limit load are both constant, the loading rate and frequency have the same variation trend. In fact, relationship between loading rate and crack growth rate decides the fatigue life. When the loading rate is too high, the internal microcracks will not have enough time to expand, then

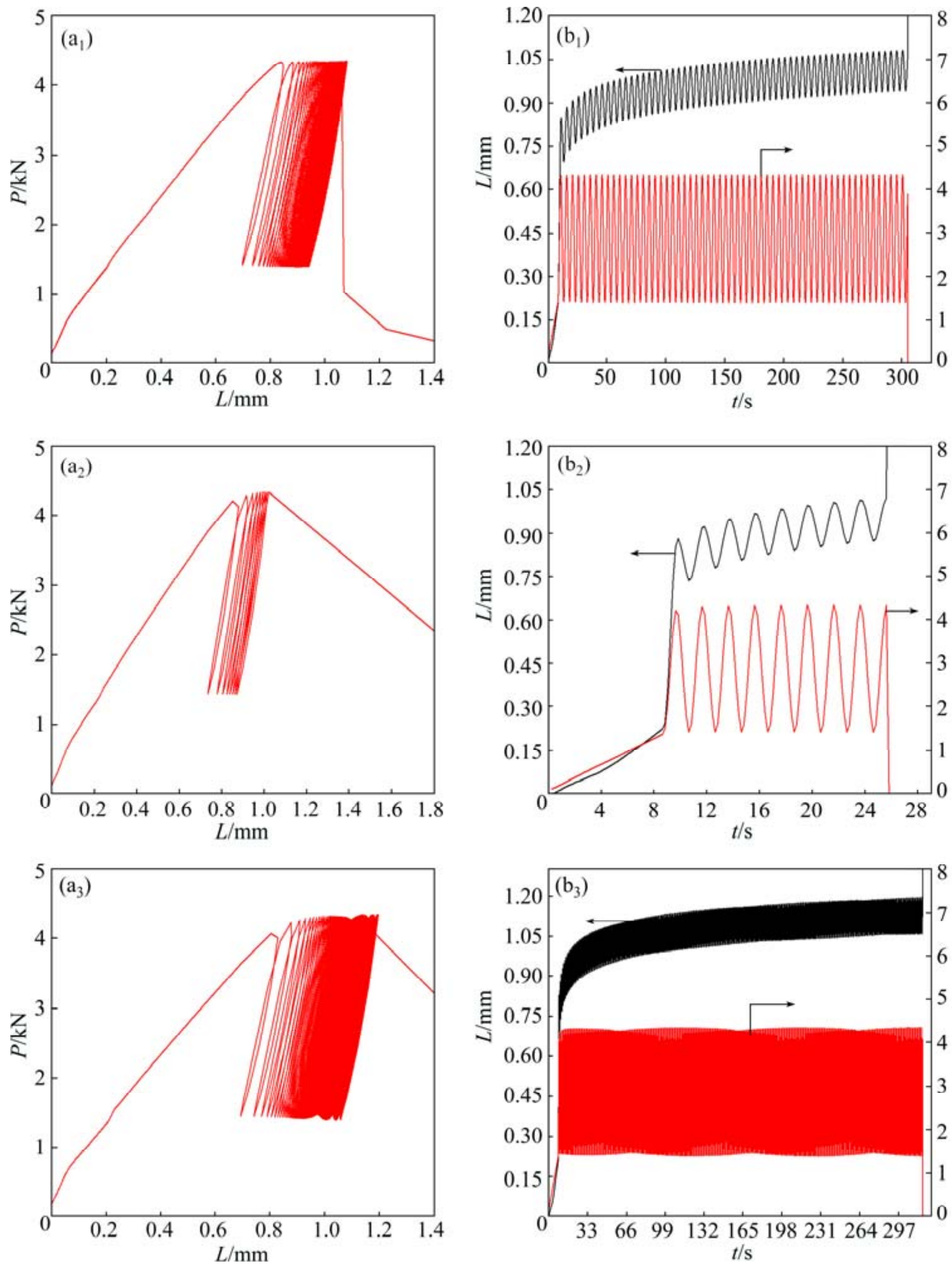

Fig. 5 Fatigue curves under different frequencies: (a_1,b_1) Sample D-5-3, 0.2 Hz; (a_2,b_2) Sample D-2-1, 0.5 Hz; (a_3,b_3) Sample D-3-2, 1 Hz

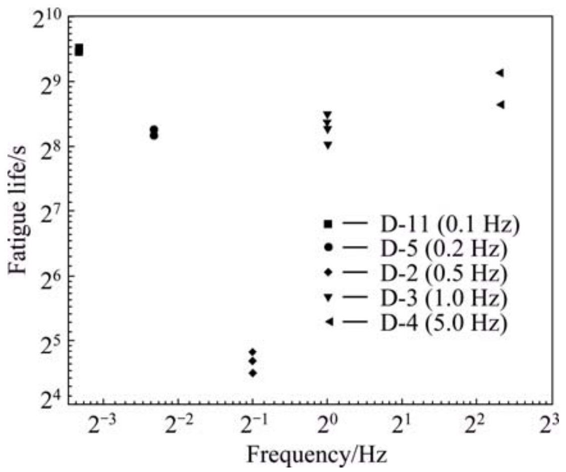

Fig. 6 Relationship between fatigue life and frequency

the resistance needed to overcome for microcracks will be big, and the input energy can be relative low; when the loading rate is too low, however, microcracks generated by current load cycle will close before the next load cycle, which also results in big resistance and low energy utilization. Under these two extreme conditions, the speed of rock fragmentation is low and the fatigue life is long. In order to break the rock quickly, the loading rate should be neither too high nor too low. That is to say, only when the loading rate falls within a certain range, can the fatigue life be the shortest. This is the reason that the fatigue life falls down first and then rises up with increasing the loading rate in this work.

3.1.2 Effect of lower limit load on fatigue life

The effect of lower limit load on fatigue life was also studied. Figure 7 gives some typical relation curves

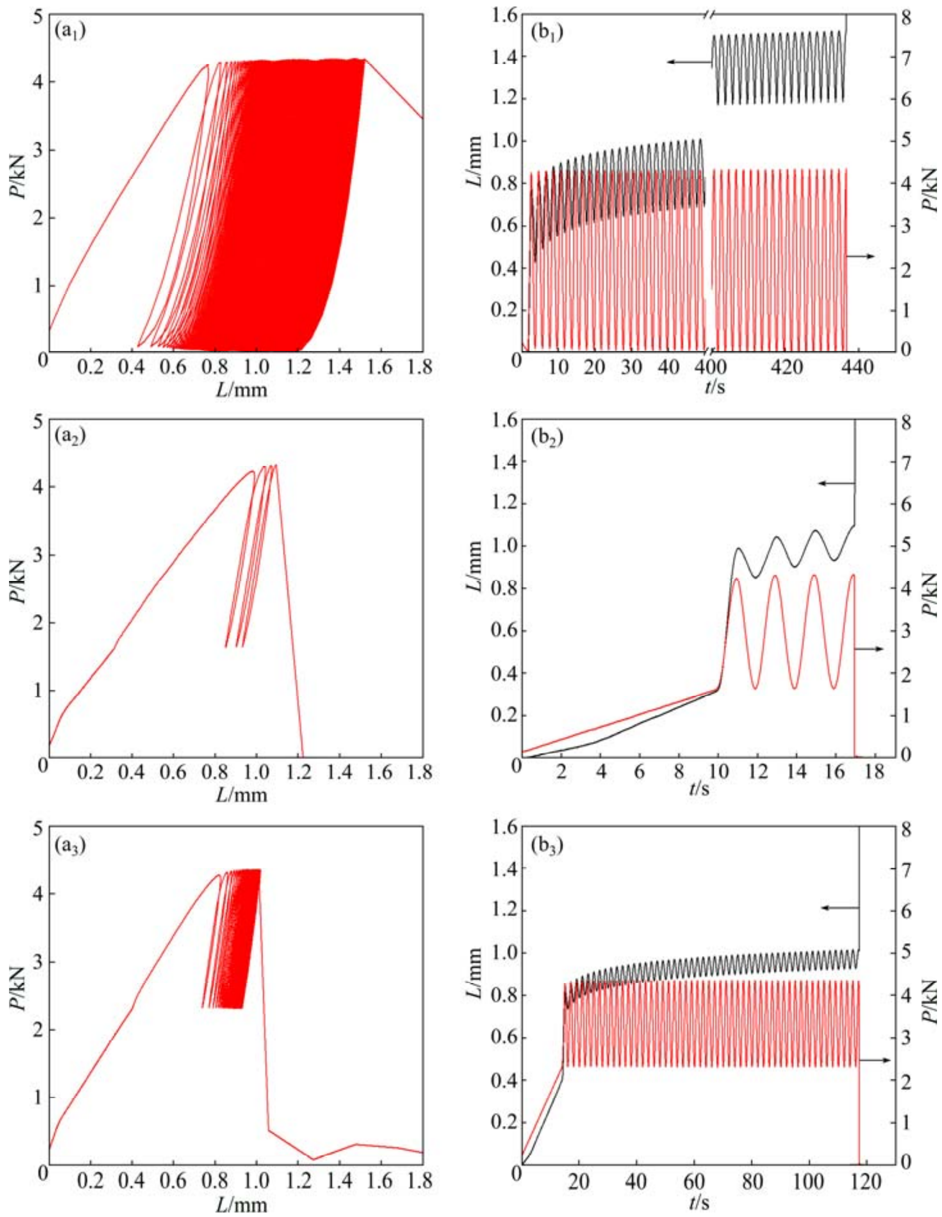

Fig. 7 Fatigue curves under different lower limit load ratios: (a_1,b_1) Sample D-1-1, lower limit load ratio of 0; (a_2,b_2) Sample D-7-1, lower limit load ratio of 0.35; (a_3,b_3) Sample D-12-1, lower limit load ratio of 0.5

of axial load (P) and penetration (L) under different lower limit loads. We can see that, fatigue lives of specimens under lower limit load ratios of 0, 0.35 and 0.50 are 436.6, 16.9 and 117.3 s, respectively. More results are shown in Fig. 8. It is seen that the fatigue life falls down first and then rises up with increasing the lower limit load ratio. The best lower limit load ratio (R_{min}) of rock-breaking, which results in the minimum fatigue life, locates in the vicinity of 0.35.

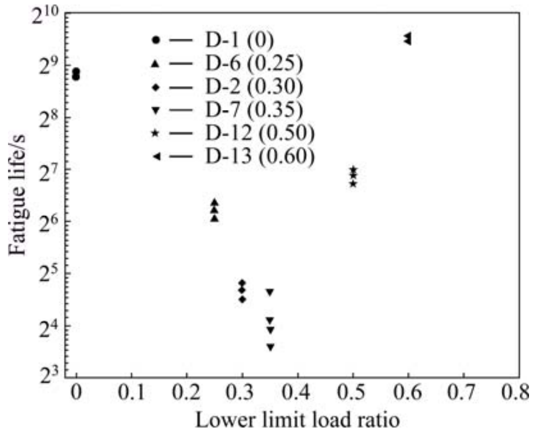

Fig. 8 Relationship between fatigue life and lower limit load ratio

As the upper limit load and frequency are constant, the amplitude will decrease with increasing the lower limit load, which then causes the decrease of the loading rate. As explained in Section 3.1.1, the fatigue life falls down firstly and then rises up with increasing the loading rate. So, the effect of lower limit load ratio on rock's fatigue life can be described by Fig. 9.

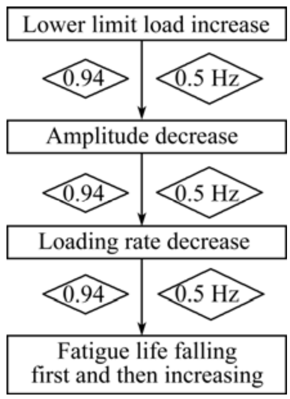

Fig. 9 Flow chart of effect of lower limit load on fatigue life

3.2 Hysteresis property

During cyclic point loading tests, the penetration formed a hysteresis loop in each load cycle. The loops changed their slopes and density gradually with increasing the cycle number, and were affected by the lower limit load and frequency. Here, the change details of the hysteresis loops are demonstrated.

3.2.1 Effect of frequency and lower limit load on hysteresis loop

As shown in Fig. 10, taking Specimen D-6-2 as example, there are 34 hysteresis loops during the whole deformation. Each hysteresis loop began from the upper limit load, passing around the lower limit load, and ended when the load reached the upper limit load again. With the increase of cycle number, the loops seemed to become denser.

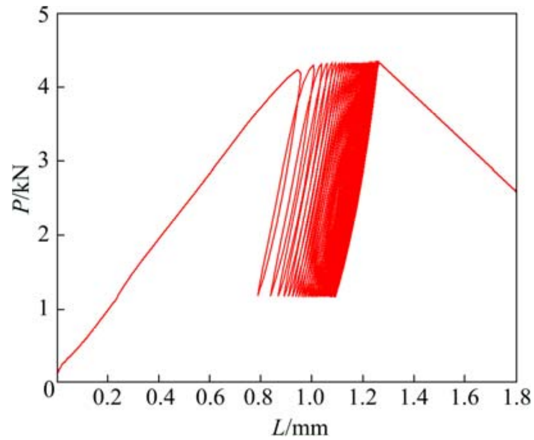

Fig. 10 Fatigue curve of Specimen D-6-2 at 0.25−0.5 Hz

In Fig. 11, the hysteresis loops of cycles 1, 2, 3, 4, 11, 12, 13, 14, 21, 22, 23, 24, 31, 32, 33 and 34 are drawn. The results indicate that the areas of these loops are almost unchanged, but their spacing becomes closer and closer.

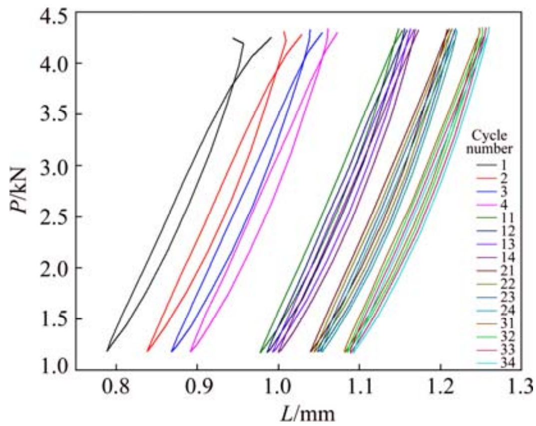

Fig. 11 Hysteresis loops of chosen cycles of Specimen D-6-2

In order to illustrate the spacing between hysteresis loops quantitatively, curves of the spacing against cycle number of specimens under different load conditions are presented in Fig. 12, the horizontal axis of which is a base-2 logarithm axis. Here, the spacing is expressed by the increment of penetration at the lower limit load for every neighbouring loop. For Specimen D-4-1, as there are too many load cycles, only results before cycle 350 are shown. It can be seen that the loop spacing decreases with the increase of the cycle number generally. Under the same cycle number, the spacing increases with rising the frequency and decreasing the lower limit load ratio.

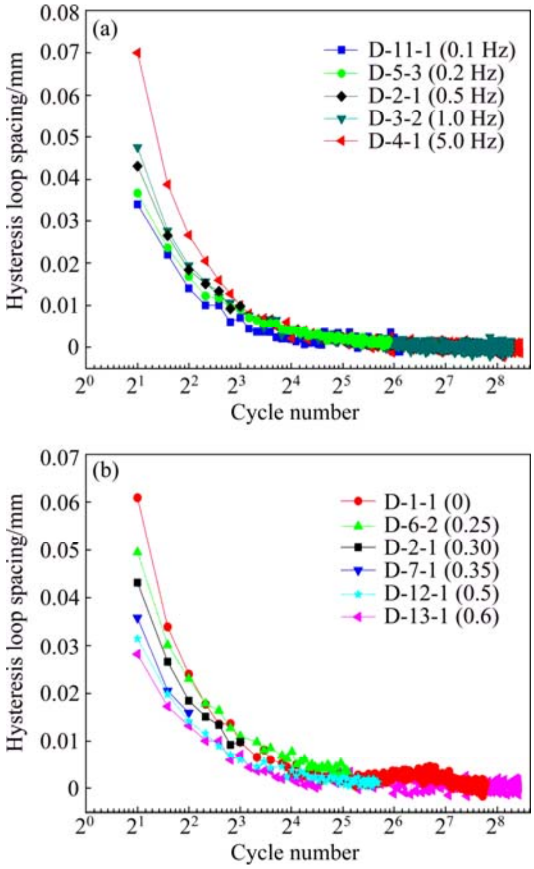

Fig. 12 Tendency of hysteresis loop spacing again cycle number in semi-log coordinate system: (a) At different frequencies; (b) At different lower limit load ratios

Figure 13 gives the double base-2 logarithmic diagrams of hysteresis loop spacing against cycle number. According to Fig. 13(a), the loop spacing of Specimen D-2-1 decreases linearly with increasing the cycle number and fails quickly at cycle 8. For Specimens D-11-1, D-5-3, D-3-2 and D-4-1, the loop spacing decreases linearly firstly and then big fluctuation appears before failure. For specimens under different lower limit load ratios, as can be seen in Fig. 13(b), the loop spacing also decreases linearly with the increase of cycle number. And the fluctuation can also be checked for some specimens like D-1-1, D-12-1 and D-13-1. According to the laboratory observation and test data, the fluctuation of loop spacing may be caused by the local damage around the contact zone between the loading cone and rock specimen. In some tests, small rock pieces could be found flying from the cone tip when the loading frequency or amplitude was high. To some extend, the initiation of the fluctuation can serve as a good way to forecast the initial failure of rocks.

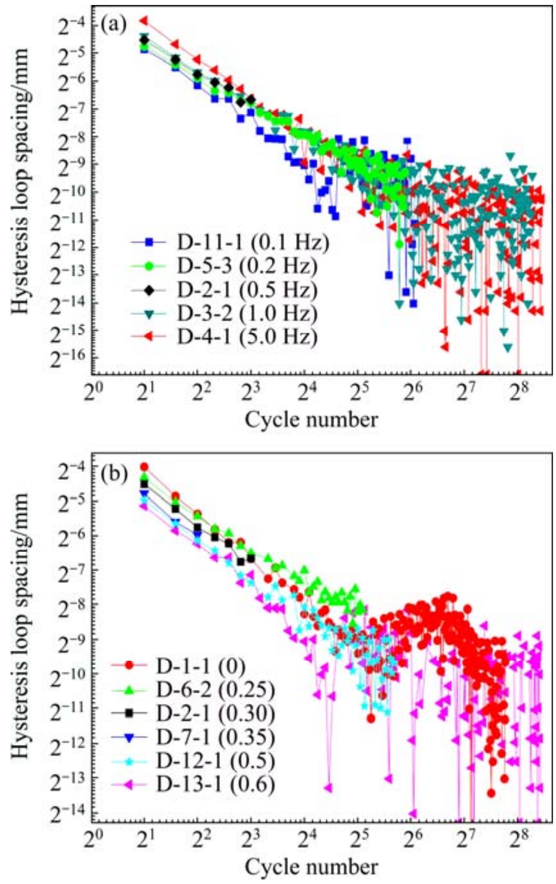

Fig. 13 Tendency of hysteresis loop spacing again cycle number in double-log coordinate system: (a) At different frequencies; (b) At different lower limit load ratios

3.2.2 Development of penetration

In Fig. 14, the penetration and its change rate with load cycle for Specimen D-6-2 are presented. We can see that the penetration rises rapidly till cycle 18, where it is up to 90% of the total penetration. Then the increase velocity of it slows down gradually. The cumulative amount of the following penetration is very small, less

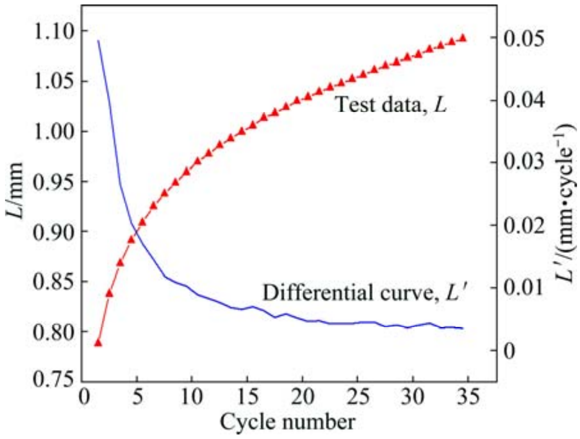

Fig. 14 Penetration (L) and its change rate (L') for Specimen D-6-2

than 10% for this case, but the time needed occupies most of the fatigue life.

In order to further study the effect of lower limit load ratio and frequency on the evolution of penetration, relations of penetration and cycle number for other specimens are also given in Fig. 15. For Specimen D-4-1, as there are too many load cycles, only results before cycle 350 are shown. The tendencies of the penetration under different loading conditions are similar, that is to say, it increases rapidly first, and then slows down gradually. For some specimens, such as D-6-2, D-2-1, and D-7-1, they fail quickly after the rapid rise-up of the penetration. But for other specimens like D-4-1, and D-13-1, they can bear load for a long time when the penetration reaches its peak value. Specimen D-1-1, however, has a relatively low starting point and high increasing velocity of penetration. The reason for Specimen D-1-1 having a low starting point of penetration comes from the fact that this specimen has low limit load ratio of 0. The penetration is mainly caused by the internal dislocation and deformation of the specimen. When the initial pre-load is low, the starting value of penetration is definitely low. While for other specimens with non-zero low limit loads, even when the specimens are unloaded, the non-zero low limit load will cause additional deformation. So, the total penetration has comparatively larger values.

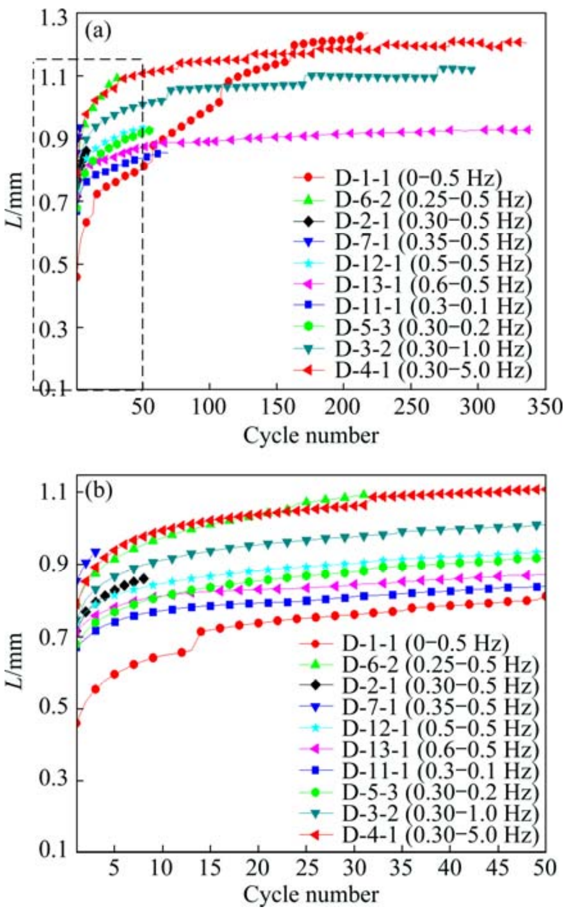

Fig. 15 Penetration under different loading conditions: (a) Complete figure; (b) Local view of (a)

Figure 16 shows the results of penetration in the semi base-2 logarithmic coordination according to the loading frequency and lower limit load ratio. Good linear correlation between the penetration and loading condition can be observed. Under careful check, discontinuous steps can also be found in some curves like D-3-2 and D-1-1. Similar to the analyses in Section 3.2.1, these discontinuous points may be indicators for local failure of specimen during tests.

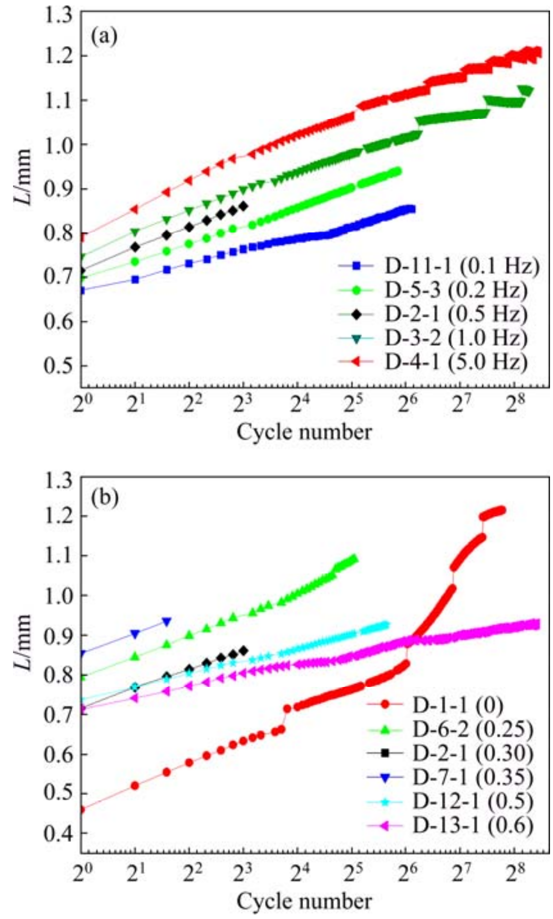

Fig. 16 Penetration under different loading conditions in semi-log coordinate system: (a) At different frequencies; (b) At different lower limit load ratios

3.3 Training and memory effects under cyclic point loading

Under multi-level cyclic loading tests, rocks are found to have training and memory effects sometimes [17]. In our tests, these effects were also checked.

In Fig. 17, Curve J-1 is a representative result from the static point load tests. Curve D-10-2 is a typical result of Specimen D-10-2 under increasing multi-level cyclic loading. The loading parameters are described in Section 2.2. It can be seen that the specimen failed at the fourth cycle of the fifth load gradient. In the fifth load gradient, the peak load is 5 kN, which is higher than the static point load strength of 4.628 kN. The fact of specimen's failure after three cycles in the fifth load gradient indicates that the specimen can bear 5 kN load to some extent. That is to say, the cyclic loading history increases the overall strength of specimen. There is training effect when rock is subjected to cyclic point loadings.

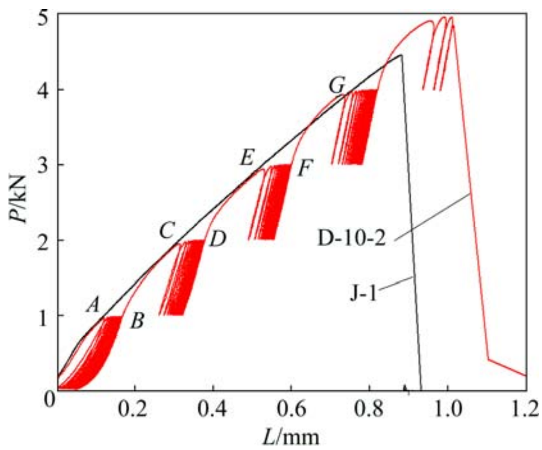

Fig. 17 P(axial load)−L(penetration) curves of specimens under static and increasing multi-level cyclic loading

In the first load gradient (0−1 kN) of Fig. 17, we can see that the specimen is firstly loaded to Point A, and deforms in the same path of the static load. Then, it is subjected to the 20th cycle loading and unloading processes and deforms to Point B. Although Point B is away from the deformation curve of static test, when the cyclic loading moves to the next gradient (1−2 kN), the deformation Point C of the first cycle falls on to the static deformation curve again. For the third and fourth load gradients, it can also be seen that Points E and G all fall on the static deformation curve. That is to say, the line joining Points A, C, E and G up will follow the same path of P−L curve of the static test. This means that rock still has memory effect when it is subjected to multi-level cyclic point loadings.

4 Conclusions

1) Under cyclic point loading, the fatigue life of sandstone decreases first and then increases with the increase of frequency and lower limit load ratio, that is to say, there exist best load frequency and amplitude for rock-breaking. For the rock type and test conditions of this study, the best frequency and lower limit load ratio values are 0.5 Hz and 0.35, respectively.

2) Under cyclic point loading, the penetration forms a hysteresis loop in each load cycle. With the increase of cycle number, the areas of these loops are almost unchanged, but their spacing becomes closer and closer. Generally, the hysteresis loop spacing decreases and the penetration increases with increasing the cycle number. Sometimes, the hysteresis loop spacing and penetration may change with great fluctuation. These fluctuations can serve as indicators of local failure of rocks during deformation.

3) Training and memory effects also exist when rocks are subjected to cyclic point loading.

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循环点荷载作用下红砂岩的力学性能

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摘 要：利用 MTS Landmark 伺服加载试验对砂岩开展循环点荷载试验并对其力学特性进行研究。试验包含恒幅循环加载和荷载逐渐增加的多级循环加载两种方式，其加载频率和下限荷载比的变化范围分别为 0.1~5 Hz 和 0~0.60。分析加载频率和下限荷载比对红砂岩疲劳寿命和滞回特性的影响。结果显示：红砂岩疲劳寿命随加载频率和下限荷载比的增加呈现先减后增的变化规律；在相同循环次数下，滞回环间距随加载频率的增大和下限荷载比的减小而不断增加。同时，红砂岩在循环点荷载作用下仍存在“锻炼”和“记忆”效应。

关键词：红砂岩；循环点荷载；疲劳寿命；滞回环；侵入；锻炼效应；记忆效应

(Edited by Wei-ping CHEN)