Investigation and modeling on fatigue damage evolution of rock as a function of logarithmic cycle

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SUMMARY

The fatigue damage behavior of granite under constant and variable amplitude loadings is studied. The experimental analysis reveals that there is a three-stage law for the fatigue damage evolution as a function of absolute or relative cycle and the inverted-S damage model proposed by the author, in this case, is capable of representing the damage behavior of rock. However, when the logarithmic cycle is considered, there are only two stages, i.e. steady and accelerated stages and the fatigue damage evolution greatly depends on the properties of rock and stress level. Accordingly, the fatigue damage evolution curves have been categorized into three types. Then, the effect of maximum stress, amplitude and fatigue initial damage on the damage evolution of rock is investigated. The analysis reveals that the damage evolution greatly depends on these influencing factors. The fatigue life decreases with the increase in the maximum stress, amplitude and fatigue initial damage due to the decrease in the proportion of the first stage to the whole fatigue process and the increase in the damage rate in the first stage. Meanwhile, a linear-exponential formula is used to model the fatigue damage behavior of rock subjected to cyclic loading. This damage model is superior to the inverted-S damage model in the convenience of establishment of critical instability point. The physical meanings of its constants have been illuminated and the applicability of this model to constant and variable amplitude cyclic loading explored. The fitting results for the test data show that this damage model can properly represent the fatigue damage behavior of rock. Copyright © 2010 John Wiley & Sons, Ltd.

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KEY WORDS: rock; fatigue damage; cyclic loading; inverted-S model

1. INTRODUCTION

Dynamic loads, such as earthquake, blasting, drilling, traffic etc., are frequently encountered in rock engineering. It is well known that cyclic loading often causes rock to fail at a stress lower than its determined compressive strength under monotonic conditions and the failure often occurs in a sudden manner. Therefore, adequate knowledge on the mechanical response of rock to cyclic loading can help the engineer to predict accurately the residual life of an existing structure or to build a stable one capable of avoiding accidental disaster.

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During the past few years, considerable efforts have been made to study the response of rock to cyclic loading. Attewell et al. [1] tried to describe the mechanism of rock fatigue in terms of strain energy-dependent crack propagation. The basic argument was that above a stress level at which cracks were initiated, deformation from successive sub-failure load cycles would be cumulative, and failure would occur when the strain energy stored in the specimen exceeded a critical energy level equivalent to failure under non-cyclic loading. Ray et al. [2] reported that the percentage decrease in the uniaxial compressive strength increases with applied stress level and cycles. The failure strength and Young’s Modulus increase with the strain rate, and the ultimate strain at failure also depends on the strain rate. Lee et al. [3] investigated the fundamental mechanisms of joint asperity degradations and their effects on the cyclic shear behaviors of irregular rough rock joints. The experimental results showed that the cyclic shear behavior of rough joint, such as peak shear strength, unequal frictional resistance for forward and backward shear displacements and non-linear dilation, were significantly affected by the second-order asperities degradation in the first shear loading cycle, but affected by the first-order asperities in the subsequent cycles. Alexander Lavrov [4] observed the Kaiser effect in a brittle limestone subjected to cyclic loading with different loading rates. It was found that damage formed during loading with a slow (high) rate can be successfully revealed by reloading with a high (slow) rate. Li et al. [5] studied the mechanical properties of jointed rock subjected to cyclical loading and reported that the deformation modulus of rock increases and the irreversible deformation decreases with the loading frequency. Meanwhile, the dynamic deformation increases with joint density and decreases with a joint angle. Gatelier et al. [6] focused on the influence of structural anisotropy on the mechanical behavior of a sandstone under cyclic compression test. There are two inelastic mechanisms, namely compaction and microcracking, during cyclic tests. Both mechanisms were influenced by the initial anisotropy due to the depositional nature of the rock. Jafari et al. [7] studied the variation of the shear strength of rock joints due to cyclic loadings. It was found that the shear strength was affected mainly by the number of loading cycles and stress amplitude during small cyclic loading and was also affected by the dilation angle, degradation of asperities and wearing during large cyclic displacement. Li et al. [8] conducted a set of experimental study and analysis for saturated, frozen, sandstone with intermittent cracks. It was concluded that the strength of the frozen samples is lower than that of the regular ones and higher than that of the saturated ones. Freezing reduces the fatigue effect and the loading frequency effect. Al-Shayea [9] analyzed the variation of elastic modulus and Poisson’s ratio during loading, unloading and reloading, and proposed a method to establish the initial elastic modulus. Ge et al. [10], Zhang Q.X. et al. [11] found that the terminal strain of fatigue failure was equal to that of post-peak corresponding to the maximal cyclic load. There was also a three-stage evolution law in the axial deformation and a two-stage law in the radial deformation. Xiao et al. [12] studied the effect of loading conditions on the mechanical properties of rock and summarized that the larger the maximum stress, amplitude and loading frequency are, the shorter the fatigue life (i.e. the number of cycles to failure) is. The fatigue life under sine waveform was longer than that under ramp waveform but shorter than that under square waveform. Bagde et al. [13, 14] found that the dynamic fatigue strength, dynamic axial stiffness and average Young’s modulus of rock decrease with loading frequencies and amplitude. The dynamic energy was found to be independent of the testing conditions and the dynamic energy sustained by the rock showed an increasing trend with frequency and amplitude.

Of course, one of the main purposes of studying the mechanical properties of rock subjected to cyclic loading is to master the law of fatigue damage accumulation and derive an applicable damage model for rock materials, which are the key issues to establish the method of fatigue life estimation. Accordingly, based on a lot of experimental investigations, the authors have proposed an inverted-S damage model [15] for describing the fatigue damage evolution. However, further investigation illustrates that there is no three-stage law on fatigue damage evolution in semi-logarithmic coordinate system and it is discommodious to obtain the critical instability point. An effort, therefore, has been made through this work to explore the fatigue damage evolution law and establish a new damage model for representing the damage evolution of rock as a function of logarithmic cycle.
2. FATIGUE DAMAGE EVOLUTION OF ROCK

The tested rock is granite from the HengYang region located in the south central China. Its modal composition is: quartz 25%, feldspar 55%, mica 14% and chlorite 6%. Samples of granite were drilled out of blocks from the same stratum. Each sample was prepared into cylinders according to the ISRM standards with a diameter of 50 mm and a length to diameter ratio equal to 2:1.

The tests were conducted on a servo-hydraulic rock testing apparatus, RMT-150B. Six specimens were applied static load with a loading rate of 0.1 kN/s and the average static strength is 143.43 MPa. The remainder of the specimens were subjected to cyclic compression under load control mode with a sinusoidal loading waveform and a frequency of 0.2 Hz. The cyclic test is composed of two steps: the first static loading step with a rate of 0.1 kN/s equal to that in static test and the second cyclic loading step with the given loading waveform and frequency. For variable amplitude cyclic loading, two types of loading programs are performed. As shown in Figure 1, one is to change the amplitude while keeping the average stress constant, and the other is to change the maximum stress while keeping the minimum stress constant.

When modeling the fatigue damage evolution of rock, the definition of damage variable should first be taken into account. It is well known that many measurements can be used to define the damage variable, such as elastic modulus, hardness, ultrasonic wave velocity, density, residual strength, residual strain, electrical resistance, energy dissipation and acoustic emission, etc. Authors [16] have analyzed six common definition methods and stated that the residual strain method is a more suitable one in the laboratory. So, the residual strain method is utilized here.

A typical three-stage evolution curve, shown in Figure 2, can be obtained as the damage variable is defined by the residual strain method and the fatigue damage is plotted as a function of absolute or relative cycle. Its evolution law coincides well with the actual degradation process of material, i.e. the initiation, stable and unstable propagation of microcracks. In this case, the inverted-S damage model proposed by the author can be used to describe the damage behavior of rock. However, one
wonders if there is also three-stage law in damage evolution when taking the logarithmic cycle as abscissa.

Figures 3 and 4 show the damage evolution curves of rock specimens subjected to constant and variable amplitude cyclic loading as a function of logarithmic cycle. It can be found that the curves exhibit two-stage instead of three-stage developing trend. In the first stage, the fatigue damage increases linearly with the increase in cycle approximately and this stage takes a great proportion of the whole fatigue life. In the second stage, the fatigue damage evolves nonlinearly at different convergence rate to failure for different rock specimens. For example, the instability of specimens F1-12 and F1-17 is a relatively slow process, whereas that of specimens F1-14, F1-18, F1-24 and F1-25 occurs in a sudden manner.

The comparison of damage evolution curves when the absolute and logarithmic cycles are taken respectively as abscissa, as shown in Figure 5, shows that the transient stage only exists when taking absolute cycle as abscissa but not when taking logarithmic cycle as abscissa. The damage
Figure 4. Damage evolution curves as a function of logarithmic cycle under variable amplitude cyclic loading.

Figure 5. Comparison of damage evolution curves with absolute and logarithmic cycles.

evolution curve is incapable of reflecting the early rapid micro-crack initiation stage of rock under cyclic loading. What is more, it is difficult to take the fatigue initial damage into account since \( n = 1 \) while \( \ln(n) = 0 \).

Of course, there are certain advantages as the fatigue damage evolution is considered as a function of logarithmic cycle. First, Similar to the rock creep analysis, our attention is focused on the accelerated stage in practice, so the fatigue damage evolution curves of rock can also provide sufficient information for engineering projects when the logarithmic cycle is taken. Second, from Figure 5, it can be seen that the point of curve 2, where the transition takes place from steady stage to accelerated stage, is a little less than that of curve 1. The cycle reservation is better able to ensure the safety of engineering. Third, the brittle rock *in situ* fails in a sudden manner without obvious deformation increase. Similar to granite specimen F1-11, the accelerated stage ends within
23 cycles, which is only 10% of the entire fatigue life. Thus, is unaware of the upcoming disaster. Obviously, the curve 2 is superior to the curve 1 in mutation performance, which is a very favorable characteristic because the upcoming disaster can be detected more easily and early.

To sum up, it is very vital and necessary to study the fatigue damage behavior of rock subjected cyclic loading as a function of logarithmic cycle. Taking into account the difficulty to describe the fatigue initial damage, one can take the damage with $\ln(n) = 0$ as an approximation, because the issue we really care about in engineering is how to determine the critical instability point.

The shape of the two-stage curve, i.e. the response of rock to different loading conditions, depends on the properties of rock and stress level. As illustrated in Figure 6, when the rock is applied high maximum stress and amplitude, the damage evolution has high damage rate and low fatigue life, as curve A. Similar to F1-12, F1-17, F1-16, F1-19 in Figure 3, the cut-off point between the steady state and accelerated state can hardly be observed. The damage behavior of rock, when the maximum stress is below the endurance limit, is manifested in the form of curve C. The damage evolution remains stable for a long time since the initial cyclic loading, that is, there is no significant increase in the first stage and the proportion of this stage to the entire fatigue life is very high. Furthermore, the rock specimen often fails suddenly. Except for these two kinds of extreme states, obvious two-stage development law like curve B can be observed in most of the experiments. These two stages can still be defined as the steady stage and the accelerated stage. Certainly, the type A can be observed hardly under variable amplitude cyclic loading, as shown in Figure 4. Owing to the existence of relatively low stress levels, the microcracks in rock can develop sufficiently and the rock fails suddenly as a whole. Thus, there are distinct two stages in the damage evolution curve.

3. THE INFLUENCING FACTORS OF DAMAGE EVOLUTION

3.1. The effect of maximum stress

When the amplitude stress level (i.e. the ratio of amplitude stress to static strength) remains constant at 0.65 and the maximum stress level (i.e. the ratio of maximum stress to static strength) is taken as 0.95, 0.93, 0.88 and 0.85, respectively, the damage evolution curves are shown in Figure 7. It can be found that as the maximum stress is set a high value, the proportion of the accelerated stage to the whole fatigue process and the damage rate of steady stage are very high. If excluding...
the effect of the fatigue initial damage, it can be concluded that the rock specimen has a short fatigue life. On the contrary, when the applied maximum stress keeps a low level, the fatigue life of rock specimen will be very long for the steady stage having a high proportion and a low damage rate. Unfortunately, it is difficult, in fact, to quantify the relation between the maximum stress and fatigue life because the response of rock is sensitive to the fatigue initial damage when the maximum stress keeps a high level. For example, since the fatigue initial damage of specimen F1-18 is of 0.0062 higher than F1-2, thus, although the applied maximum stress of F1-18 is a little lower, but its fatigue life is lower than that of F1-2. In contrast, although the fatigue initial damage of specimen F1-11 is of 0.0072 higher than F1-7, F1-11 has a longer fatigue life for its distinctly lower maximum stress.

3.2. The effect of amplitude

If the maximum stress level is fixed at 0.9, the amplitude stress level is taken as 0.7, 0.65, 0.6 and 0.55, respectively, the corresponding damage evolution curves are illustrated in Figure 12. Obviously, the proportion of the accelerated stage to the whole fatigue life increases and that of the steady stage decreases with the increase in amplitude. The damage rate of the steady stage maintains a high value. Therefore, it can be concluded that the fatigue life should be very short as the amplitude stress retains a high level. As shown in Figure 8, when the amplitude is 0.7, the first stage is difficult to be distinguished from the second and the rock specimen has a short fatigue life of 10. However, when the amplitude is 0.55, the proportion of the first stage is high and its damage rate is relatively small, and in this case the rock specimen has a long fatigue life of 1578 and exhibits an evident characteristic of brittle fracture.

3.3. The effect of fatigue initial damage

The fatigue initial damage reflects the influence from the past load history, representing the damage status before cyclic loading. A fatigue test with a given maximum stress level of 0.85 and a given amplitude stress level of 0.65 is conducted to investigate the influence of fatigue initial damage on damage evolution. From Figure 9, it can be found that there is an obvious two-stage law and a high proportion of the first stage to the whole fatigue process when the fatigue initial damage is small in magnitude. Accordingly, the fatigue life should have a decreasing trend with the increase in fatigue initial damage. The conclusion was validated by the experimental data in Figure 9.
In sum, the behavior of damage evolution largely depends on the maximum stress, amplitude and fatigue initial damage. The larger the maximum stress, amplitude and fatigue initial damage, the smaller the proportion of the first stage to the whole fatigue process, and the shorter the fatigue life of rock.

4. A NEW CUMULATIVE DAMAGE MODEL FOR ROCK

4.1. Linear-exponential damage model

From the above analysis we can see that when the logarithmic cycle is taken as abscissa, the inverted-S model is no longer applicable, and we must create a new damage model to describe the
fatigue damage evolution of rock. Based on the characteristics of the damage evolution curves in Figures 3 and 4, a linear-exponential damage model is proposed by authors.

\[ D = D_0 + a \cdot \ln(n) + b \cdot e^{(\ln(n) - x_0) / t} \]  

where \( \ln(n) \) is the logarithmic cycle, and \( D \) represents the corresponding damage after \( n \) cycles under constant amplitude loading.

\( D_0 \) is fatigue initial damage, representing the damage state before fatigue loading. It is originated from the loading history before testing static loading stage and the first cycle of cyclic loading.

\( a \) is the linear damage rate. As shown in Figure 10, it represents the rate of damage evolution in the first steady stage. In general, since the number of cycles in the steady stage makes up the majority of the entire fatigue life, the value of \( a \) is directly correlated with the cycles to failure of rock.

\( x_0 \) represents the critical instability center. From Figure 11 one can see that the greater the \( x_0 \), the latter the instability of rock occurred, more cycles can be endured and the longer the fatigue life has with the rock. For hard and brittle rock, because the accelerated stage often finishes within dozens of, even several cycles, so, the parameter \( x_0 \) can be used as a reliable and convenient indicator for engineering design and on-site monitoring.

\( b \) is the instability proportion factor. As illustrated in Figure 12, it affects the proportion of the accelerated stage to the whole fatigue life. The greater the \( b \), the higher the proportion.

\( t \) is the instability velocity factor, which affects the convergence rate of damage evolution curve Figure 13. The instability of rock occurs in a very few cycles and the rock shows significant features of brittle fracture when \( t \) is small. This means that the proportion of the accelerated stage to the entire fatigue life is related to \( t \) as well as \( b \).

### 4.2. Damage evolution equation under constant amplitude cyclic loading

Figure 14 shows the fitting result for experimental data of specimen F1-18 with maximum stress level of 0.93 and amplitude stress level of 0.65. Its initial damage is up to 0.7637, which reveals the great amount of flaws inside the rock before cyclic loading. The damage rate of linear segment \( a = 0.0358 \), the instability proportion factor \( b = 0.0002 \), the critical instability center \( x_0 = 3.0533 \), the instability velocity factor \( t = 0.0442 \) and the square of correlation coefficient \( R^2 \) is as high as 0.9953. Table I lists the fitting results of all granite specimens under constant amplitude cyclic loading. Obviously, the curves are highly relevant with the laboratory experimental data. Therefore,
the linear-exponential damage model proposed by authors can describe well the fatigue damage evolution of rock.

$D_0$ is the main reason contributing to the high degree of dispersion of the fatigue mechanical properties of rock. The average fatigue initial damage of all 16 specimens is up to 0.7145 and the coefficient of variation reaches 0.13, which reveals considerable extent of damage inside rock before cyclic loading. Meanwhile, it shows that even all the specimens are drilled closely from the same rock block, there still exists significant differences between them. This damage state before cyclic loading, as well as the loading conditions such as maximum stress, amplitude, waveform and frequency, etc., affect the subsequent process of fatigue damage evolution greatly. For example, the damage rate of steady stage has a coefficient of variation of 0.3, the critical instability center 0.52 and the instability velocity factor 1.36, which results in the hundreds of differences in the fatigue life of rock specimen.
4.3. Damage evolution equation under variable amplitude cyclic loading

Specimen F1-24 is subjected to two-level cyclic loading. The maximum stress level is 0.8 and 0.85, respectively, as the minimum stress level is fixed at 0.3. The specimen is cycled to 500 at the first stress level and to failure at the second stress level. A three-level cyclic loading with an increasing maximum stress level from 0.85, 0.9 to 0.95 and a fixed minimum stress level of 0.3 is applied on the specimen F1-25. The number of cycles at the former two levels is 300 and 500, respectively, and the specimen is also cycled to failure at the third stress level.

In Figures 15 and 16, it can be seen that in the course of cyclic loading the fatigue damage is accumulated to the critical value continuously. So, it is convenient to study the whole process of rock destruction under cyclic loading from the perspective of damage. The parameter $b$ of specimen F1-24 is bigger compared with that of specimen F1-25, which means higher proportion of the accelerated stage to the fatigue life. In spite of that, the specimen F1-24 has a slightly longer fatigue life attributing to a larger critical instability center and a smaller instability velocity factor.
Table I. Fitting the results of experimental data under constant amplitude cyclic loading.

<table>
<thead>
<tr>
<th>Number</th>
<th>Number of cycles to failure</th>
<th>Max. stress level</th>
<th>$D_0$</th>
<th>$a$</th>
<th>$b$</th>
<th>$x_0$</th>
<th>$t$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1-1</td>
<td>572</td>
<td>0.92</td>
<td>0.8412</td>
<td>0.0130</td>
<td>0.0225</td>
<td>7.5710</td>
<td>1.2694</td>
<td>0.9961</td>
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<tr>
<td>F1-2</td>
<td>125</td>
<td>0.95</td>
<td>0.7575</td>
<td>0.0250</td>
<td>0.0364</td>
<td>4.3674</td>
<td>0.4030</td>
<td>0.9925</td>
</tr>
<tr>
<td>F1-4</td>
<td>49</td>
<td>0.90</td>
<td>0.6740</td>
<td>0.0284</td>
<td>0.0667</td>
<td>3.7987</td>
<td>0.0802</td>
<td>0.9848</td>
</tr>
<tr>
<td>F1-5</td>
<td>3065</td>
<td>0.85</td>
<td>0.5721</td>
<td>0.0201</td>
<td>0.0592</td>
<td>7.8995</td>
<td>0.1117</td>
<td>0.9451</td>
</tr>
<tr>
<td>F1-6</td>
<td>109</td>
<td>0.90</td>
<td>0.5816</td>
<td>0.0266</td>
<td>0.0950</td>
<td>4.5996</td>
<td>0.0888</td>
<td>0.9791</td>
</tr>
<tr>
<td>F1-7</td>
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<td>0.95</td>
<td>0.6765</td>
<td>0.0243</td>
<td>0.0274</td>
<td>4.9941</td>
<td>0.0458</td>
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<tr>
<td>F1-9</td>
<td>1185</td>
<td>0.90</td>
<td>0.6919</td>
<td>0.0238</td>
<td>2.9E-24</td>
<td>6.8992</td>
<td>0.0035</td>
<td>0.9936</td>
</tr>
<tr>
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<td>10</td>
<td>0.90</td>
<td>0.8628</td>
<td>0.0323</td>
<td>0.0071</td>
<td>1.3649</td>
<td>0.4274</td>
<td>0.9978</td>
</tr>
<tr>
<td>F1-11</td>
<td>230</td>
<td>0.95</td>
<td>0.6837</td>
<td>0.0194</td>
<td>0.0168</td>
<td>5.3997</td>
<td>0.0157</td>
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<tr>
<td>F1-12</td>
<td>1578</td>
<td>0.90</td>
<td>0.7168</td>
<td>0.0200</td>
<td>0.0016</td>
<td>7.2986</td>
<td>0.0146</td>
<td>0.9797</td>
</tr>
<tr>
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<td>0.85</td>
<td>0.8475</td>
<td>0.0134</td>
<td>0.0093</td>
<td>2.9417</td>
<td>0.5015</td>
<td>0.9934</td>
</tr>
<tr>
<td>F1-15</td>
<td>94</td>
<td>0.85</td>
<td>0.6547</td>
<td>0.0191</td>
<td>0.0880</td>
<td>4.4981</td>
<td>0.0429</td>
<td>0.9888</td>
</tr>
<tr>
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<td>0.0197</td>
<td>0.0476</td>
<td>1.5791</td>
<td>0.4152</td>
<td>0.9981</td>
<td></td>
</tr>
<tr>
<td>F1-18</td>
<td>28</td>
<td>0.7637</td>
<td>0.0358</td>
<td>0.0002</td>
<td>3.0533</td>
<td>0.0442</td>
<td>0.9953</td>
<td></td>
</tr>
<tr>
<td>F1-20</td>
<td>7</td>
<td>0.90</td>
<td>0.5925</td>
<td>0.0368</td>
<td>0.0008</td>
<td>1.5242</td>
<td>0.0695</td>
<td>0.9999</td>
</tr>
<tr>
<td>F1-23</td>
<td>20</td>
<td>0.85</td>
<td>0.7164</td>
<td>0.0323</td>
<td>0.0088</td>
<td>1.4000</td>
<td>0.2874</td>
<td>0.9935</td>
</tr>
</tbody>
</table>

Figure 15. Damage evolution of rock under two-level cyclic loading.

in magnitude. Furthermore, the specimen F1-24 fails in a shorter period of time, having more obvious characteristic of brittle fracture.

Table II lists the fitting results of all granite specimens under variable amplitude cyclic loading. The fitting results suggest that the fitting curves are highly relevant with the laboratory experimental data, that is, the proposed damage model is well suited to describe the damage evolution of rock under variable amplitude cyclic loading.

5. CONCLUSION

(1) A set of cyclic tests with constant amplitude or variable amplitude have been carried out. From the experimental results, it can be found that there is a two-stage evolution law for fatigue damage of rock as a function of logarithmic cycle. The damage in the first stage is of a linear increase with the growth of cycles and the proportion of this stage to the entire fatigue life is
relatively high in most cases. In the second stage, the fatigue damage evolves nonlinearly at different convergence rates to failure. The shape of the two-stage curve, i.e. the response of rock to different loading conditions, depends greatly on the properties of rock and stress level. Based on the experimental results, the fatigue damage evolution curves have been categorized into three types by the authors.

(2) A set of experiments have been planned elaborately to study the effect of maximum stress, amplitude and fatigue initial damage on the damage evolution of rock subjected cyclic loading. The results reveal that the damage evolution greatly depends on these influencing factors. The fatigue life decreases with the increase in the maximum stress, amplitude and fatigue initial damage due to the decrease in the proportion of the first stage to the whole fatigue process and the increase in the damage rate in the first stage. In spite of which, it is difficult, in fact, to quantify the relation between the stress level and fatigue life for the existence of fatigue initial damage.

(3) Based on the two-stage law of fatigue damage evolution and three categories of evolution curves, a linear-exponential damage model is proposed in this work. The physical meanings of its
constants have been illuminated and the influence of these constants to the damage evolution curve has been studied. The fitting results for the test data under constant amplitude cyclic loading and variable amplitude cyclic loading show that this damage model can properly represent the damage behavior of rock subjected to cyclic loading.

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