

Research Article

Evaluating Long-Term Strength and Time to Failure of Sandstone with Different Initial Damage

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Long-term strength (LTS) of rock materials is important for the long-term stability analysis and the failure prediction of structures in rock engineering. Numerous studies have been carried out on the LTS for various kinds of rock; however, the effects of initial damage on the LTS and creep failure time of rock have not been conducted. In the present study, the creep experiment with controllable initial damage state of rock was designed. Then, the LTS of rock specimens with different initial damage was determined by four methods (i.e., the isochronous stress-strain curve method, the steady creep discriminated method, the volumetric strain inflexion point determined method, and the intersection of the steady creep rate method). The results show that, with the increase in the initial damage, the LTS of rock decreases and the relationship between the initial damage and the LTS of rock can be described as a linear function. Finally, an evaluation method for predicting the creep failure time of rock under a single stress level was proposed. In addition, the creep failure time of rock with different initial damage under different creep stress levels was obtained by the method. The results indicate that both the initial damage and the creep stress levels have a great influence on creep failure time, i.e., greater initial damage or creep stress leads to a shorter period for rock failure. Thus, for analyzing the long-term stability of rock mass structure, not only the influence of in situ stress but also the initial damage state of the surrounding rock should be considered.

1. Introduction

The design and construction of rock engineering, such as high slope rock engineering, underground oil or gas storage project, and underground cavern rock engineering, should be considered for the analysis of the long-term stability of rock mass structures. However, LTS of rock materials is the key mechanical parameter to analyze the long-term stability and service lifespan of these rock structures [1–3]. It was considered as a stress threshold, which can be used for analyzing the time-dependent crack propagation in rock and predicting the time-dependent deformation of engineering structures [4–8].

Excavation is a common activity of rock engineering (e.g., caverns in hydropower stations and roadways in

underground coal mines). During the excavation, the redistribution of in situ stress in the surrounding rock will lead the rock mass to undergo different levels of damage at different depths [9–11]. Thus, in order to analyze the long-term stability and predict the lifespan of rock structure, it is necessary to determine the LTS of rock with different initial damage. However, there are few research studies on the relationship between the initial damage and the characteristics of the time-dependent behavior of rock. In view of this, a study for evaluating the LTS and time to failure of rock materials with different initial damage is very significant.

At present, a lot of methods have been proposed to determine the LTS of rock based on the experimental and theoretical research studies, such as the isochronous stress-strain curve method, the steady creep discriminated method,

and the volumetric strain inflexion point method [5, 12–16]. Martin and Chandler [17] pointed out that the LTS of rock corresponded to the stress of microcrack-induced dilation, and Chandler [13] further defined the stress at volumetric strain reversal as the LTS based on the results of creep tests. Shen and Chen [18] put forward a method to predict the LTS and the failure time of rock by the combination of creep curves and stress-strain curves. Nara et al. [19, 20] pointed out that the subcritical crack growth is related to the LTS of rock and examined the subcritical crack growth of rock to evaluate the LTS. Although a lot of research studies have been carried out to determine the LTS of rock and failure time, the previous studies primarily focused on the intact rock and paid little attention to the rock materials with initial damage.

In the present study, the effect of initial damage on the LTS and creep failure time of rock was investigated. First, a creep test scheme of rock with controlled initial damage was proposed. Then, based on the experimental data, the LTS of rock with different initial damage was investigated by the common methods and the intersection of the steady creep rate method proposed in this study, respectively. Finally, a unified set of methods to determine the creep failure time of rock at different creep stress levels was proposed, and the influence of creep stress levels and initial damage on rock failure time was analyzed.

2. Experimental Investigation

2.1. Rock Specimens and Experimental Apparatus. The rock specimens used in the present experimental study were sourced from intact sandstone blocks, which are characterized by brown-red, coarse grain structure and uniform texture. They were prepared as cylindrical samples with a diameter of 50 mm and a length of 100 mm (Figure 1), in accordance with the standard proposed by ISRM [21]. All the rock specimens for the experiments in this study need to be carefully selected. At first, the rock specimens which have the obvious flaws (cracks, pores, and inclusions) on the surface were dismissed. Then, the longitudinal wave velocity of the remaining rock specimens was tested, and its average value is 2830 m/s. The specimens with wave velocities from 2730 m/s to 2930 m/s were selected for the next testing.

The tests were conducted on the thermal-hydro-mechanical-chemical (THMC) coupling testing system, with a maximum axial loading capacity of 1500 kN, designed by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. The apparatus allowed maximum values of confining pressure and pore pressure of 60 and 30 MPa, respectively. Two linear variable displacement transducers (LVDTs) and a chain collar are used to measure the axial and circumferential deformation. The test apparatus is shown in Figure 2.

2.2. Experimental Method. The basic mechanical properties of rock samples are the basis for setting up the following test scheme. Then, three samples were selected for uniaxial compressive tests of sandstone to obtain the basic mechanical parameters. The average values of uniaxial



FIGURE 1: Rock sample of sandstone.

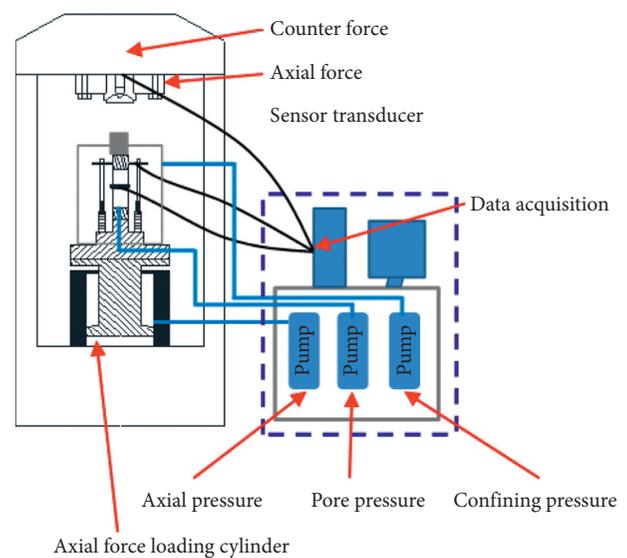


FIGURE 2: THMC coupling testing system.

compressive strength, Young's modulus, and Poisson's ratio of the sandstone are 39.2 MPa, 9.68 GPa, and 0.27, respectively. The standard deviations of the uniaxial compressive strength, Young's modulus, and Poisson's ratio are 1.26 MPa, 0.15 GPa, and 0.04, respectively. Thus, it can be considered that the samples selected in the test have good homogeneity.

The stress-strain curve of the sandstone was obtained through the uniaxial compressive test, and it is shown in Figure 3. According to the observation of the stress-strain curve, the deformation characteristics of the sandstone can be divided into four regions (crack closure, elastic region, crack stable growth, and unstable cracking) before failure [22]. Hence, the rock samples with controllable initial damage can be obtained by the loading-unloading tests. In order to obtain the different levels of initial damage by the loading-unloading tests, one stress unloading level was set in the stress region of crack stable growth and three unloading levels were set in the unstable cracking stress region (Figure 3). The four unloading stress levels correspond to approximately 65%, 80%, 90%, and 98% of the average peak strength, respectively, and they are shown in Table 1.

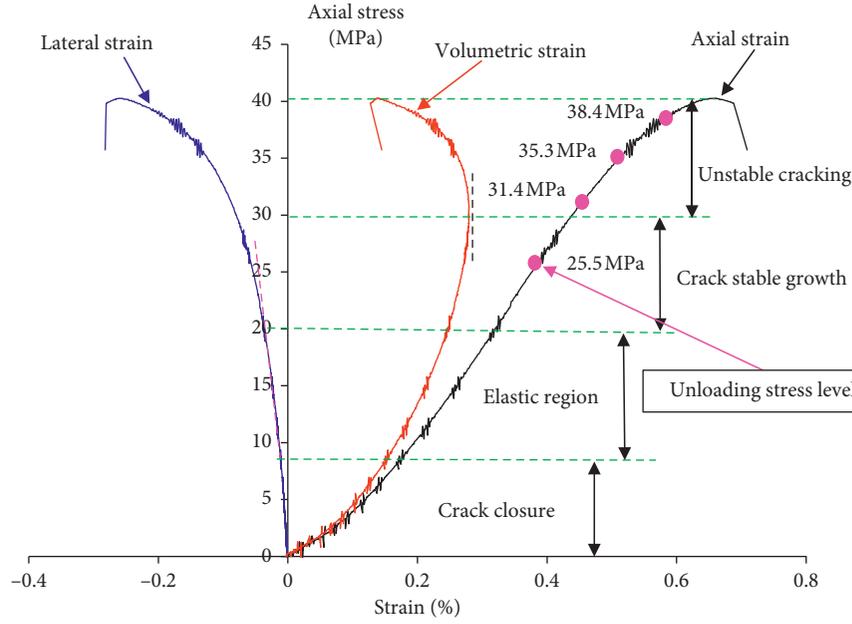


FIGURE 3: Stress-strain curve of sandstone and unloading stress levels.

TABLE 1: Unloading stress and creep stress levels.

Unloading stress (MPa)	Creep stress (MPa)							
	1st	2nd	3rd	4th	5th	6th	7th	8th
25.5	15.7	19.6	23.5	27.4	29.4	31.4	33.4	35.4
31.4	15.7	19.6	23.5	27.4	29.4	31.4	33.4	35.4
35.3	15.7	19.6	23.5	27.4	29.4	31.4	33.4	35.4
38.4	15.7	19.6	23.5	27.4	29.4	31.4	33.4	35.4

In order to obtain the time-dependent behavior characteristics of rock with different initial damage, the creep tests should be conducted. As a result, the loading and unloading have little effect on the compressive strength of rock [23]. Thus, eight axial stress levels (Table 1) were put forward in the creep tests, based on the average peak strength. In the creep tests, the creep stress was held constant 24 h at each stress level, until the rock specimen fails. The creep test process of rock with controllable initial damage state is as follows:

- (1) The specimen was loaded to 30% of the average peak strength (11.7 MPa) and unloaded completely to obtain the irreversible deformation caused by crack compaction. This step is important for making damage rock samples and can reduce the impact of primary cracks in the samples on the evaluation of the initial damage state of rock.
- (2) The specimen was loaded to the predetermined unloading stress level and unloaded completely to obtain the residual deformation. It can be used to evaluate the initial damage of the rock specimen. The definition of the initial damage of rock is described in Section 2.3.

- (3) During the creep experiments, the creep stress is set at eight levels based on the average values of the uniaxial compressive strength of rock, which are shown in Table 1. Then, the creep tests are conducted by the multistage loading method. The specimens with different initial damage will last for 24 hours at each stress level until the failure occurs.

2.3. Experimental Results. In order to analyze the influence of initial damage on the LTS of rock, the definition of initial damage of rock is needed to be put forward first. In the present study, based on the damage law proposed by Xie et al. [24], the damage equation related to the variation of strain and unloading modulus was determined as follows:

$$D_{\text{inid}} = 1 - \frac{\varepsilon - \varepsilon_r}{\varepsilon - \varepsilon_u} \left(\frac{E_u}{E} \right), \quad (1)$$

where D_{inid} is the initial damage variable of rock, ε is the total axial strain, ε_u is the crack compression strain obtained by the test procedure, ε_r is the axial residual strain after unloading, E_u is the unloading modulus, and E is the elastic modulus of rock. Based on equation (1), the values of the initial damage variable for each rock specimen were

calculated, and they are listed in Table 2. According to the values of the initial damage variable, the specimens with different initial damage in these tests were denoted as D_1 , D_2 , D_3 , and D_4 (shown in Table 2), where $D_1 < D_2 < D_3 < D_4$.

Figure 4 shows the strain-time curves of rock specimens with different initial damage, where the axial compression is positive and the lateral expansion is negative, respectively. The results indicate that the time-dependent deformation of rock is significantly affected by the creep stress levels. When the creep stress levels are below the creep failure stress (i.e., the final creep stress level), the time-dependent deformation can be divided into two stages, a primary creep stage with decreasing strain rate and a steady creep stage with a constant strain rate. At the final creep stress level, three creep stages (i.e., primary creep, secondary creep, and tertiary creep) are observed, except the specimen with initial damage D_1 .

From Figure 4, it can also be seen that the initial damage has a significant effect on the creep behavior of rock. When the creep stress levels are less than 27.4 MPa, the time-dependent deformation characteristics of specimens with different initial damage states are similar at the same stress level. However, under the condition of high creep stress levels (i.e., higher than 27.4 MPa), it shows that the rock specimens that contain the larger initial damage will express the more obvious creep characteristics.

In addition, the results indicate that the specimens with initial damage D_1 , D_2 , D_3 , and D_4 undergo five, six, seven, and eight levels of loading until creep failure, respectively. The time to failure (i.e., creep failure time) was 168.4, 149.9, 124.2, and 110.1 h for the specimens with initial damage D_1 , D_2 , D_3 , and D_4 . By comparing the duration of tests before creep failure of different specimens, it can be inferred that the rock with larger initial damage will be more prone to creep failure under the same temperature, stress, and other conditions.

For the designs of rock engineering projects, if the influence of initial damage of rock on the time-dependent behavior (especially the LTS of rock) is not considered, it would overestimate the long-term stability of the rock mass structures. In other words, the designs may lead to instability in rock mass if the LTS is overestimated. Therefore, it is very important to accurately obtain the LTS of rock with different initial damage states for the long-term stability analysis and lifespan prediction of rock mass engineering.

3. LTS Analysis of Rock with Different Initial Damage

At present, the LTS of rock is mostly obtained by analyzing the creep test results in the laboratory. The analysis methods used commonly include the isochronous stress-strain curve method, the steady creep discriminated method, and the volumetric strain inflexion point determined method. However, various analytical methods have different definitions for the LTS, and there may be a few deviations in the results. Therefore, in this study, not only the three common methods were used to evaluate the LTS of rock with different initial damage, but also the intersection of the steady creep

rate identified method was proposed to obtain the LTS of rock quantitatively.

3.1. Common Methods for Evaluating LTS of Rock

3.1.1. Isochronous Stress-Strain Curve Method. The isochronous stress-strain curve method is the most widely used method to determine the LTS of rock. The isochronous stress-strain curve shows the relationship between the strain and the creep stress of rock specimens at different stress levels, when it sustains equal time. The axial isochronous stress-strain curves can be used to confirm the LTS of rock in general, but it has poor applicability for hard rocks with little axial deformation [25]. From Figure 4, it can be found that distinct lateral time-dependent deformation can be observed when the creep stress levels are more than 27.4 MPa. Moreover, Cui and Fu [25] pointed out that the LTS of rock determined by the lateral isochronous stress-strain curves is safer for engineering applications. Therefore, according to the procedure introduced by Tan [26], the lateral isochronous stress-strain curves of rock with different initial damage were drawn, as shown in Figure 5.

It can be seen from Figure 5 that the time parameter of the isochronous stress-strain curves is 4, 8, 12, 16, and 20 hours at each creep stress level. The isochronous curves show obvious nonlinear characteristics when the inflexion point appears. But it is difficult to accurately determine the inflexion point in the curves by the limited test data and duration of the test. Thus, it means that the LTS of rock can only be obtained in a certain stress range. According to the analysis of the curves, the LTS of rock specimens with initial damage D_1 , D_2 , D_3 , and D_4 is considered at the stress range from 27.4 to 29.2 MPa, 26 to 28 MPa, 25.5 to 27.4 MPa, and 23.4 to 24.6 MPa, respectively.

3.1.2. Steady Creep Discriminated Method. When using the steady-state creep discriminated method to estimate the LTS of rock, the value of LTS is considered to be consistent with the maximum creep stress that can keep the steady creep strain rate at zero. According to the results of multistage loading creep tests, the creep curves of rock specimens with different initial damage at each creep stress levels are obtained, and they are shown in Figure 6. It can be seen from the figure that the steady creep is observed at the creep stress level of 29.4 MPa, for the rock specimen with initial damage D_1 , and the steady creep of the rock specimens with initial damage D_2 , D_3 , and D_4 is observed at the same creep stress level (27.4 MPa). Therefore, it can be inferred that the LTS of rock with the initial damage D_1 is in the stress range from 27.4 to 29.4 MPa, and the LTS of rock with the initial damage D_2 , D_3 , and D_4 is from 23.5 to 27.4 MPa. In addition, if the interval of the creep stress level is set large, the LTS of rock with different initial damage cannot be obtained accurately by the steady creep discriminated method. Quite evidently, it is difficult to obtain the critical stress when the steady creep occurs by analyzing the creep curve.

TABLE 2: Values of the initial damage variable for different specimens.

Initial damage state	Unloading stress (MPa)	Value of initial damage
D_1	25.5	0.036
D_2	31.4	0.227
D_3	35.3	0.383
D_4	38.4	0.505

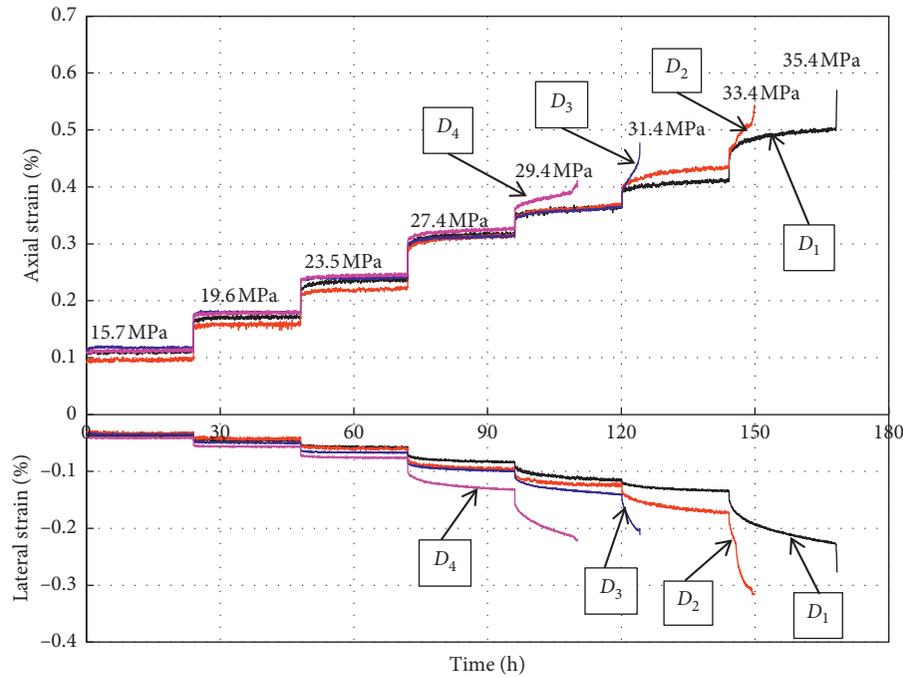


FIGURE 4: Creep test results of rock with different initial damage.

3.1.3. Volumetric Strain Inflexion Point Determined Method. Rock failure is related to the unstable propagation of internal cracks [19]. When the creep stress is more than the stress threshold of unstable cracking, the internal crack propagates greatly until rock failure with the increase in time. The existing research studies have shown that the unstable propagation of cracks is related to the volumetric dilatancy of rock, and the stress corresponding to the volumetric strain inflexion point of volumetric strain curves in the creep test can be considered as the LTS of rock [13, 17].

The relationship between the volumetric strain and the creep time of rock specimens with different initial damage is shown in Figure 7. It can be seen that there are two obvious volumetric strain inflexion points in the curves (i.e., point “A” and “B” in Figure 7). The creep stress level at the inflexion points is 27.4 and 29.4 MPa, respectively. However, the appearance of the volumetric strain inflexion point may be related to the setting of the creep stress level in the multistage loading creep tests. Therefore, 27.4 and 29.4 MPa cannot be regarded as the value of LTS for the rock specimens.

According to the creep stress levels and the volumetric strain inflexion points in the curves in Figure 7, the stress range of LTS can be determined. When the creep stress level

is 29.4 MPa, the volumetric strain inflexion point of the rock specimen with initial damage state D_1 appears. Thus, it can be concluded that the LTS of the rock specimen with initial damage D_1 is in the range from 27.4 to 29.4 MPa. By observing the relationship between volumetric strain and time of specimens with initial damage D_2 , D_3 , and D_4 , it can be found that the creep stress level corresponding to the volumetric strain inflexion points is 27.4 MPa. Then, it can be further inferred that the LTS of the rock specimens with initial damage D_2 , D_3 , and D_4 is in the range from 25.3 to 27.4 MPa. According to the above analysis, it is difficult to quantitatively obtain the LTS of rocks with different initial damage by the volumetric strain inflexion point determined method.

3.2. Quantitative Evaluation Method of LTS. As mentioned above, the LTS of rock can be considered as the stress corresponding to the volumetric strain inflexion point in creep tests. In practice, it is difficult to quantify the LTS of rock relying on the volumetric strain curves obtained from the creep tests. In order to accurately determine the LTS of rock with different initial damage, the method of identifying the intersection of the axial and lateral steady creep rate is

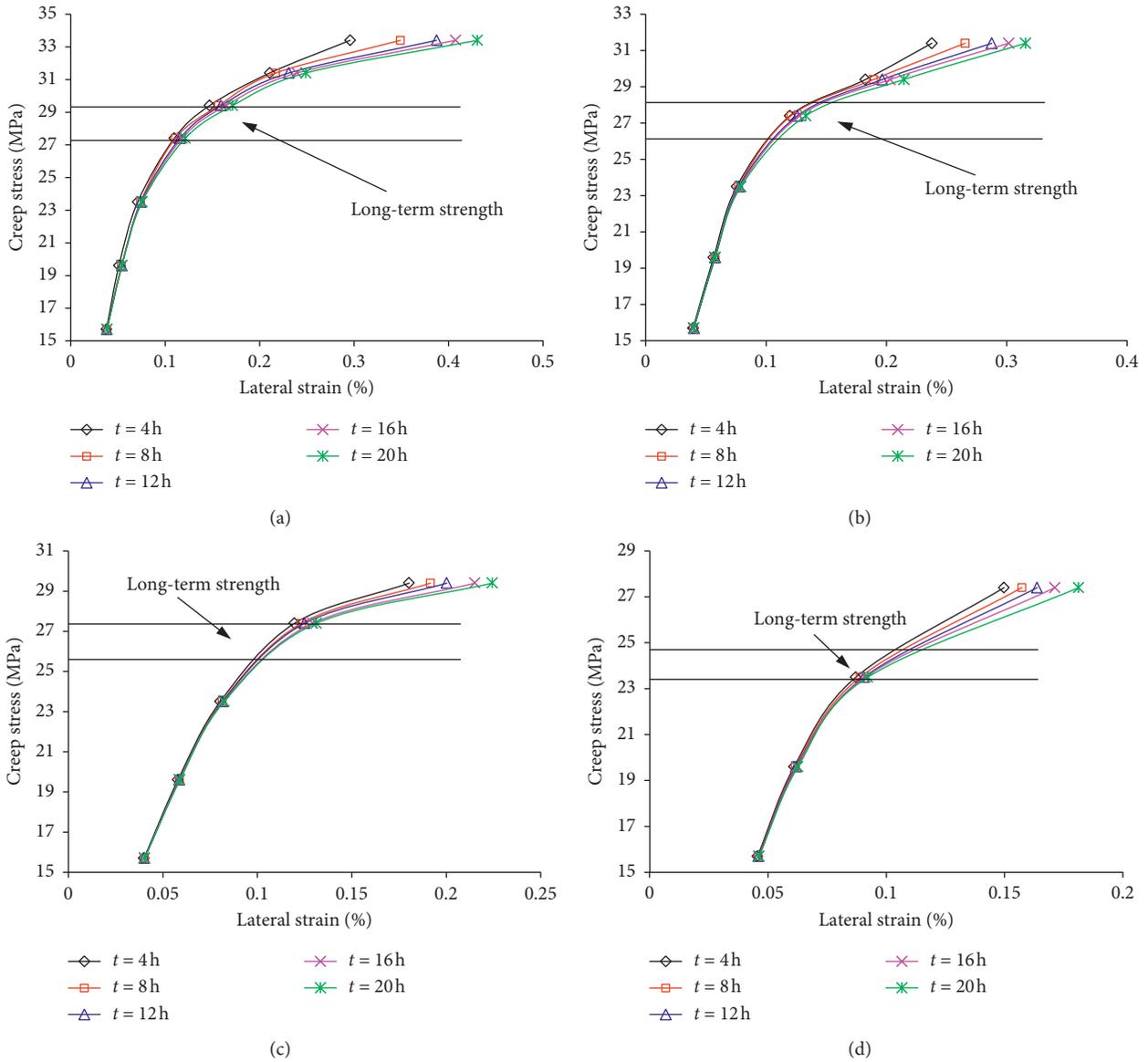


FIGURE 5: Lateral isochronous stress-strain curves of rock specimens with different initial damage: (a–d) the rock specimens with initial damage state D_1 , D_2 , D_3 , and D_4 , respectively.

proposed. The results of the creep tests in this study show that if the creep stress is less than the stress threshold of volumetric dilatancy, the steady creep rate of the axial is more than that of the lateral. With the increase in the creep stress, the steady creep rate increases, and the lateral strain increases more significantly than the axial strain (Figure 4). At this time, the lateral steady creep rate is more than the axial steady creep rate, and an intersection of the axial and lateral creep rate curves can be found. Therefore, in the curves of the relationship between the strain rate and the creep stress, the stress corresponding to the intersection of the steady creep rate is the stress threshold of volumetric dilatancy, which is also generally considered as the LTS of rock.

Figure 8 shows the relationship between the steady creep rate (axial and lateral) and the creep stress of rock specimens

with different initial damage. Then, the exponential function was used to fit the data, and the intersections of axial and lateral steady creep rates are obtained. The stress values corresponding to the curve intersections are the LTS of rock specimens with different initial damage, and they are listed in Table 3. The results in Table 3 indicate that the LTS is affected by the initial damage of rock. With the increase in the initial damage of rock, the LTS decreases.

Figure 9 shows the relationship between the initial damage and the LTS of rock specimens. The results indicate that the relationship between the LTS and the initial damage of rock is approximately linear. In addition, it can be inferred from Figure 9 that the LTS is 29.226 MPa when the initial damage variable value of rock is zero. In this case, the value of LTS is close to the stress corresponding to the volumetric strain flexion point in the stress-strain curve (Figure 3).

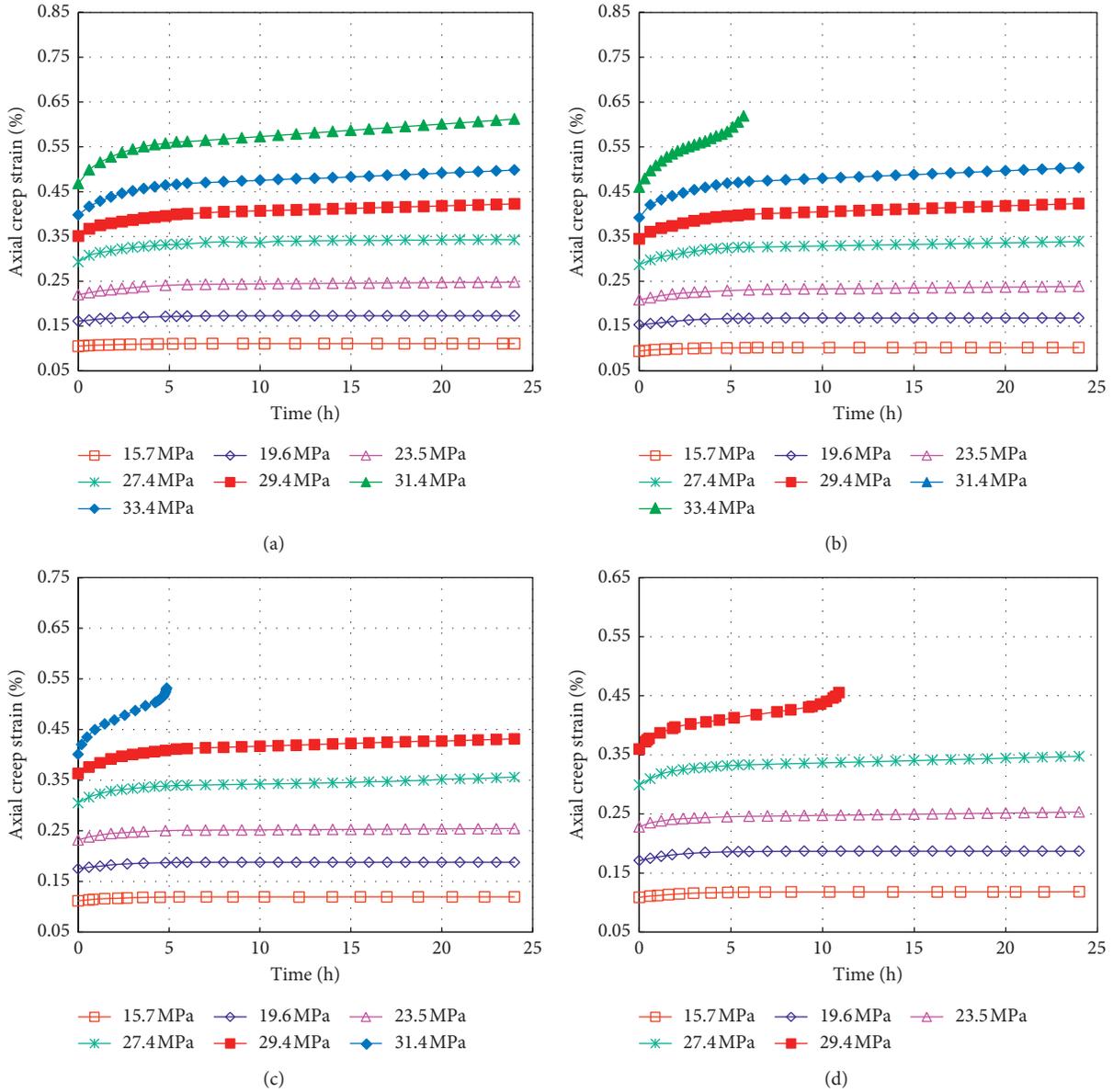


FIGURE 6: Creep curves of rock specimens with different initial damage: (a–d) the rock specimens with initial damage state D_1 , D_2 , D_3 , and D_4 , respectively.

Therefore, the conclusion proposed by Chandler [13] that the stress corresponding to the inflexion point of volumetric strain in the stress-strain curves can be defined as the LTS of rock has been verified. Based on the above analysis, the relationship between LTS and the initial damage of rock materials can be described as follows:

$$\sigma_L = kD_{init} + \sigma_{L0}, \quad (2)$$

where σ_L denotes the LTS of damaged rock, σ_{L0} denotes the stress corresponding to the inflexion point of volumetric strain in the uniaxial compression test, D_{init} denotes the variable of initial damage, and k is the material constant.

3.3. Comparison and Discussion. In the present study, four methods are used to confirm the LTS of rock specimens with different initial damage, and the results are shown in

Table 4. It can be seen that the LTS of rock specimens cannot be accurately confirmed by using the isochronous stress-strain curve method, the steady creep discriminated method, and the volumetric strain inflexion point determined method. However, the proposed method of identifying the intersection of axial and lateral steady creep rates can be used to quantitatively determine the LTS of rock.

Comparing the four analysis methods, it is noticed that the determination of the inflexion points in the isochronous stress-strain curves is very important for evaluating the LTS of rock by using the isochronous stress-strain curve method. But it is difficult to identify the inflexion point when the rock type is hard rock or the duration of the creep test is short. It means that the LTS cannot be accurately determined under this condition, and only the stress range of LTS can be

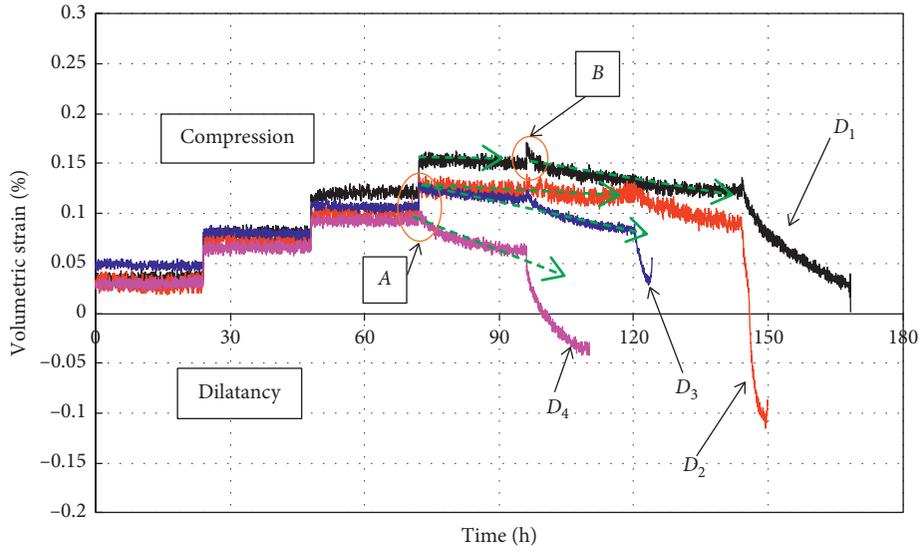


FIGURE 7: Volumetric strain curves of rock specimens with different initial damage in the creep tests.

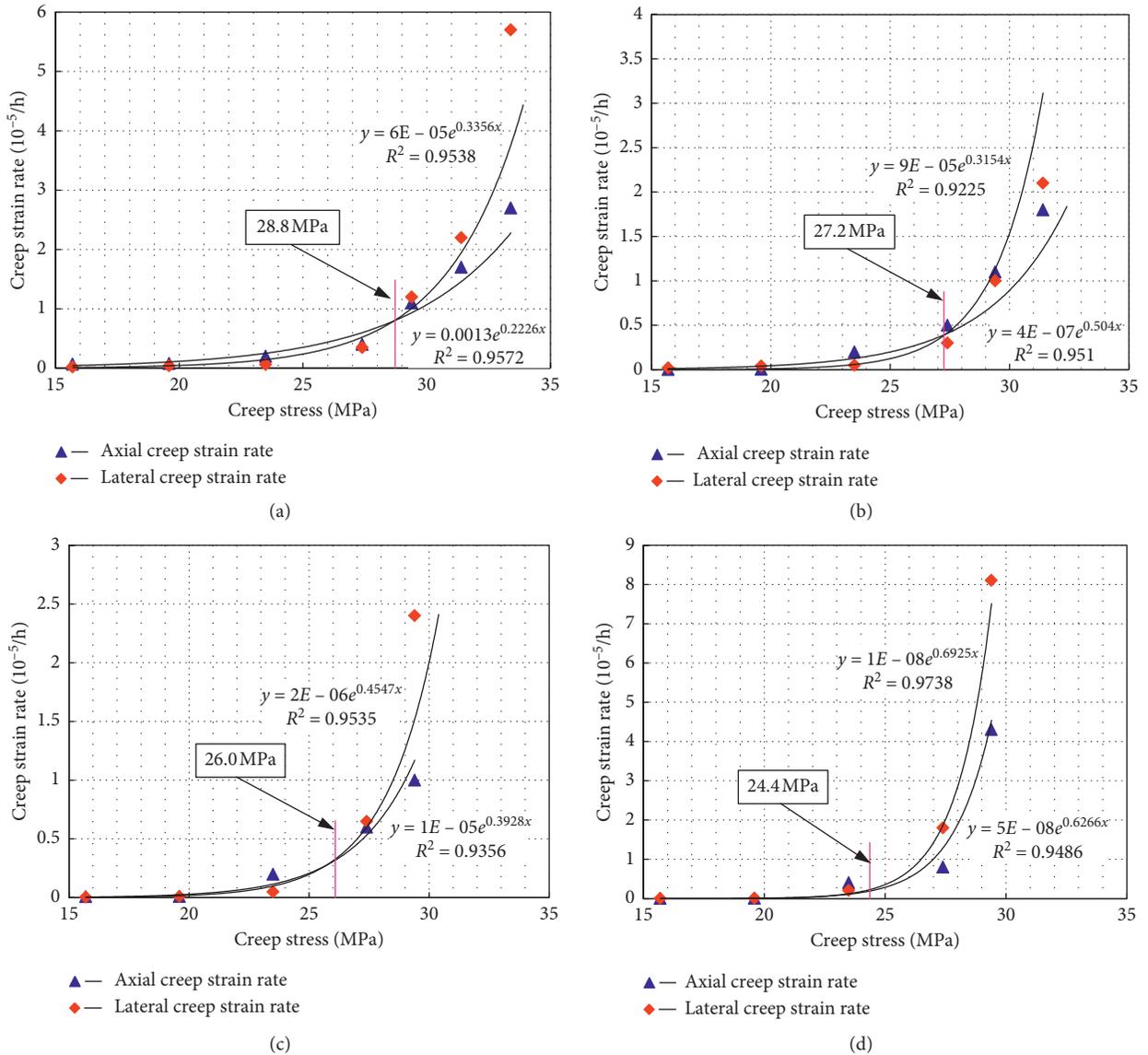


FIGURE 8: Intersection curves of axial and lateral steady creep rates of rock with different initial damage states: (a–d) the rock specimens with the initial damage state D_1 , D_2 , D_3 , and D_4 , respectively.

TABLE 3: LTS of rock specimens with different initial damage.

Initial damage state	Values of initial damage variable	LTS (MPa)
D_1	0.036	28.8
D_2	0.227	27.2
D_3	0.383	26.0
D_4	0.505	24.4

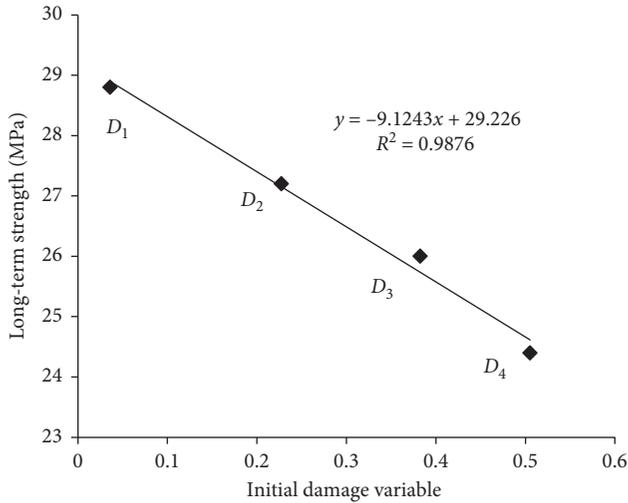


FIGURE 9: Relationship between the LTS and the initial damage of rock.

TABLE 4: LTS of rock with different initial damage obtained by four methods.

Initial damage state	LTS (MPa)			
	Method 1	Method 2	Method 3	Method 4
D_1	27.4~29.2	27.4~29.4	27.4~29.4	28.8
D_2	26.0~28.0	23.5~27.4	23.5~27.4	27.2
D_3	25.5~27.4	23.5~27.4	23.5~27.4	26.0
D_4	23.4~24.6	23.5~27.4	23.5~27.4	24.4

Note. Methods 1, 2, 3, and 4 denote the isochronous stress-strain curve method, the steady creep discriminated method, the volumetric strain inflexion point determined method, and the intersection of steady creep rate method, respectively.

confirmed. Furthermore, it can be found from Table 4 that the stress range of the LTS obtained by the isochronous stress-strain curve method is small. If the average value of the stress range is taken as the LTS, the LTS of the rock specimens with different initial damage can be quantitatively confirmed. The values of LTS are shown in Table 5. The results indicate that the value of LTS obtained by the isochronous stress-strain curve method and the intersection of axial and lateral steady creep rate method is very close. It can also prove that the LTS of rock with different initial damage obtained by the intersection of axial and lateral steady creep rate method is reliable.

When the steady creep discriminated method or the volumetric strain inflexion point determined method is used to estimate the LTS of rock, the specific value cannot be

TABLE 5: LTS value of the rock specimens obtained by methods 1 and 4.

Initial damage state	LTS (MPa)		
	Method 1	Method 4	Absolute value of difference
D_1	28.3	28.8	0.5
D_2	27	27.2	0.2
D_3	26.45	26.0	0.45
D_4	24	24.4	0.4

Note. Methods 1 and 4 denote the isochronous stress-strain curve method and the intersection of the steady creep rate method, respectively.

obtained. But, according to the results of creep tests, the stress range of LTS can be confirmed. However, it is worth noting that the range of LTS is related to the creep stress levels which are set in the creep test. For example, according to the method 2 or 3 (in Table 4), the LTS of the specimen with initial damage state D_1 is in the stress range from 27.4 to 29.4 MPa, and the LTS of specimens with the initial damage state D_2 , D_3 , and D_4 are all in the stress range from 23.5 to 27.4 MPa.

In conclusion, the isochronous stress-strain curve method and the intersection of the steady creep rate method are suitable for confirming the LTS of rock with different initial damage. Moreover, using the intersection of the steady creep rate method to determine the LTS of rock materials is not limited by the duration of the creep test.

4. Evaluating the Creep Failure Time of Rock with Different Initial Damage

Most creep tests of rock are carried out by the multistage loading. This is because the testing time can be saved and three-stage creep behavior can be obtained by the multistage loading. Based on the results obtained from the multistage loading creep tests and the creep theory, the creep model can be established to analyze the long-term stability of the rock structures. However, for the rock structure in service, the surrounding rock usually under a single constant loading state may fail after long-term creep. Therefore, it is significant for the lifespan prediction of rock engineering to study the creep failure time of rock under a single constant loading, on basis of the multistage loading creep test results. In this part, the method for predicting the creep failure time of rock with different initial damage under different stress levels was proposed. Then, the influence of initial damage and the creep stress levels on the creep failure time of rock was analyzed.

4.1. Evaluating Method of Rock Failure Time. In the creep tests, the rock specimens fail after the stage of accelerated creep. Compared with the total creep test duration, the duration of accelerated creep is little. Therefore, it is not necessary to consider the duration of the accelerated creep stage when predicting the creep failure time of rock. In addition, the creep failure of rock is related to the stress levels. It means that when studying the lifespan of rock

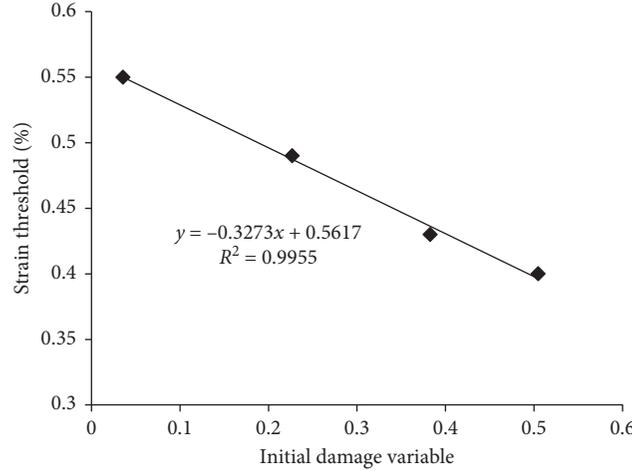


FIGURE 10: Relationship between the initial damage and the strain threshold of creep failure in the creep test.

creep, a suitable evaluation method to predict the duration of rock failure under a single stress level should be proposed.

The peak stress and strain can be used as the important mechanical parameters to analyze the failure characteristics of rock in the triaxial or uniaxial compression tests [23, 27]. Therefore, in this study, the strain corresponding to the occurrence of accelerated creep can be used as the strain threshold that is used to predict the creep failure time of rock. Based on the results of the creep tests, the relationship between the initial damage and the strain threshold of rock specimens with different initial damage is shown in Figure 10. It can be seen that the strain threshold decreases linearly with the increase in initial damage, and the relationship between them is described as follows:

$$\varepsilon_{ct} = bD_{init} + \varepsilon_{c0}, \quad (3)$$

where ε_{ct} is the strain threshold of creep failure, ε_{c0} is the strain threshold of rock without initial damage in the creep test, and b is the material constant.

In order to predict the creep failure time of rock, the relationship between the strain and time needs to be determined. In the present study, the relationship between strain and time of rock creep is usually obtained by establishing the theoretical model. The threshold strain proposed in this study is only related to the deformation of the primary and steady creep stages. Therefore, the Burgers model was selected to express the relationship between strain and time before the accelerated creep stage [28]. The equation of the Burgers creep model is as follows:

$$\varepsilon = \frac{\sigma}{E_1} + \frac{\sigma}{\eta_1}t + \frac{\sigma}{E_2} \left(1 - e^{-(E_2/\eta_2)t} \right), \quad (4)$$

where σ is the creep stress, ε is the total strain contained the instantaneous strain and creep strain, t is the creep time, and E_1 , E_2 , η_1 , and η_2 are the viscoelastic parameters of the Burgers model.

According to the above analysis, the failure time prediction formula (equation (5)) is proposed based on the Burgers model and the strain threshold. When a constant creep stress σ is applied, the creep failure time

can be determined according to equation (5). If the value of the constant stress is less than σ_L , no matter how long the rock is loaded, it will never fail. If the value of the constant stress exceeds σ_L , the creep failure time should be considered as the duration when the creep strain exceeds the strain threshold:

$$\begin{cases} t = \infty, & \sigma \leq \sigma_L, \\ \left\{ \frac{\sigma}{E_1} + \frac{\sigma}{\eta_1}t + \frac{\sigma}{E_2} \left(1 - e^{-(E_2/\eta_2)t} \right) = \varepsilon_{ct}(D_{init}), \right. & \sigma > \sigma_L. \end{cases} \quad (5)$$

Additionally, when predicting the creep failure time of rock, the determination of creep model parameters in equation (5) is very important. Based on the results of the creep tests, the parameters of the Burgers model of different specimens with initial damage are identified under different stress levels (excluding the last creep stress level). The model parameters of the rock specimens with different initial damage are listed in Table 6. It can be observed that the creep parameters of different specimens have little differences at the same creep stress level. Thus, it can be considered that the creep parameters are not affected by the initial damage of rock, when the creep stress is lower than the creep failure stress (i.e., the stress level at which the accelerated creep occurs). For the convenience of application, when the creep stress is less than the creep failure stress, the average values of creep parameters of different rock specimens under the same stress level can be considered as the model parameters, and they are shown in Table 7. The relationship between the creep parameters and the creep stress is shown in Figure 11. The results indicate that the parameters of the creep model decrease with the increase in the creep stress, and the relationship between them is an exponential function. According to the relationship between the creep parameters and creep stress levels (Figure 11), the model parameters at any creep stress levels can be estimated. Then, the creep failure time can be determined by substituting the creep parameters into equation (5).

TABLE 6: Creep parameters of rock specimens with different initial damage states.

Creep stress (MPa)	Initial damage	E_1 (GPa)	E_2 (GPa)	η_1 (GPa·h)	η_2 (GPa·h)
15.7	D_1	14.9	269.5	—	483.8
	D_2	15.5	234.6	—	450.3
	D_3	14.1	244.9	—	431.1
	D_4	14.4	226.5	—	450.5
19.6	D_1	12.17	152.76	—	420.25
	D_2	12.21	139.19	—	400.32
	D_3	11.2	149.64	—	386.91
	D_4	11.46	122.55	—	396.91
23.5	D_1	10.68	103.61	—	273.68
	D_2	10.94	102.62	—	259.52
	D_3	10.13	108.66	—	233.65
	D_4	10.31	112.66	—	264.41
27.4	D_1	9.35	73.68	—	151.02
	D_2	9.55	75.11	3773	146.78
	D_3	8.98	82.67	3973.64	131.13
	D_4	9.16	88.67	3673.64	135.27
29.4	D_1	8.38	64.41	2773	123.66
	D_2	8.52	60.28	2723	124.12
	D_3	8.11	65.69	2873.64	127.97
31.4	D_1	7.89	50.13	1973	95.79
	D_2	8.01	48.13	1656	85.79

TABLE 7: Average creep parameters of rock specimens with different initial damage under different stress levels.

Creep stress (MPa)	E_1 (GPa)	E_2 (GPa)	η_1 (GPa·h)	η_2 (GPa·h)
15.7	14.7	241.4	—	453.9
19.6	11.8	143.5	—	401.1
23.5	10.5	106.9	—	257.8
27.4	9.3	80.0	3806.8	141.1
29.4	8.3	63.5	2789.9	125.3
31.4	8.0	49.1	1814.5	90.8

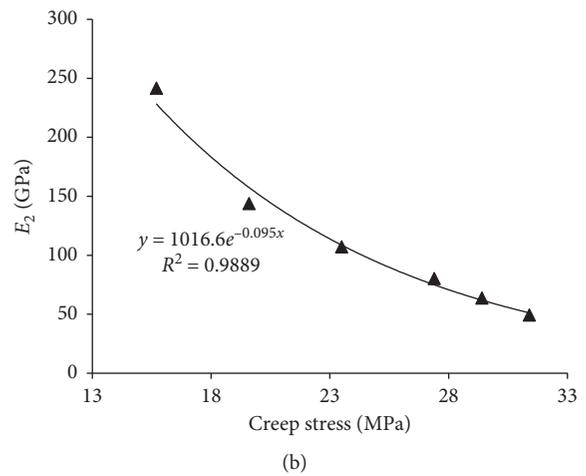
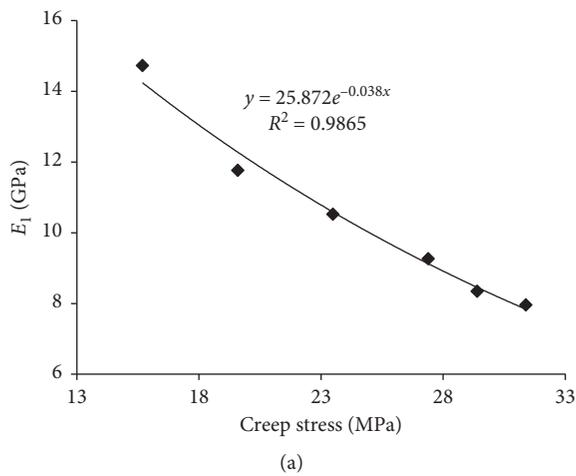


FIGURE 11: Continued.

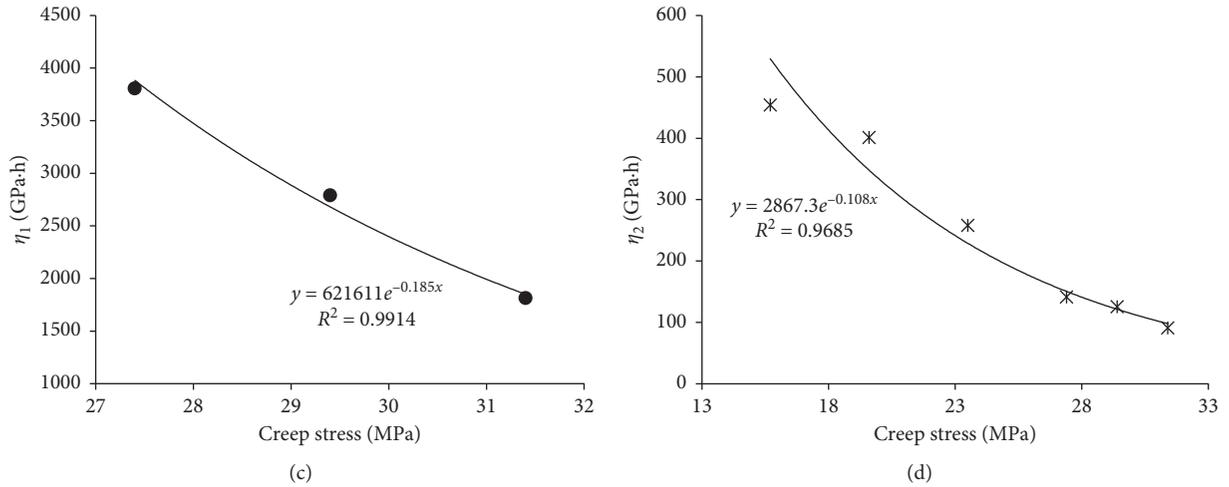


FIGURE 11: Relationship between creep parameters and creep stress: (a) E_1 ; (b) E_2 ; (c) η_1 ; (d) η_2 .

TABLE 8: Creep parameters and failure time of rock specimens with initial damage D_2 and D_3 at different creep levels.

Initial damage	Strain threshold (%)	Creep stress (MPa)	E_1 (GPa)	E_2 (GPa)	η_1 (GPa·h)	η_2 (GPa·h)	Failure time (h)
D_2	0.49	27.4	9.3	80.0	3806.8	141.1	223.85
		28.4	8.8	68.5	3248.9	133.5	143.93
		29.4	8.3	63.5	2789.9	125.3	84.92
		30.4	8.1	56.6	2244.1	107.5	45.02
D_3	0.43	27.4	9.3	80.0	3806.8	141.1	140.51
		28.4	8.8	68.5	3248.9	133.5	75.28
		29.4	8.3	63.5	2789.9	125.3	27.97
		30.4	8.1	56.6	2244.1	107.5	4.47

In view of the above descriptions, the determination procedure of creep failure time under a single constant stress is described as follows:

- (i) First, according to the creep test results of rock specimens with different initial damage and equation (2), the LTS of rock with a specific damage state is obtained.
- (ii) Next, based on the creep test curves and equation (3), the creep failure strain threshold is determined.
- (iii) Then, identifying the model parameters based on the creep test results and the Burgers model. According to the relationship between creep parameters and the creep stress, the parameters under a specific creep stress level are acquired.
- (iv) Finally, the creep failure time of rock under a single constant load is calculated by equation (5).

4.2. Effects of Creep Stress and Initial Damage on Time to Failure. In order to determine the relationship between creep stress and creep failure time, the failure time of the specimens with initial damage D_2 and D_3 is predicted, when the creep stress level is 27.4, 28.4, 29.4, and 30.4 MPa, respectively. Based on the results of creep tests and the determination procedure of creep failure time, the LTS, the strain threshold, and the model

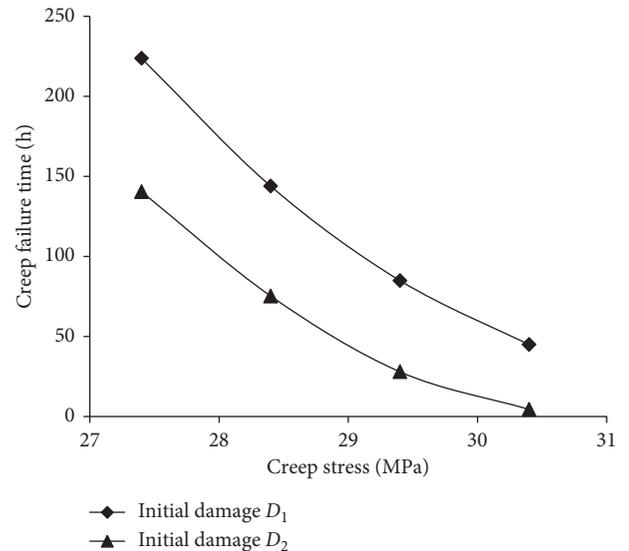


FIGURE 12: Relationship between the creep stress and the creep failure time of rock specimens with initial damage D_2 and D_3 .

parameters are obtained (Table 8). Then, the creep failure time is predicted by equation (5), and it is shown in Table 8. The relationship between the creep stress and the failure time of specimens with initial damage D_2 and D_3 is shown in Figure 12.

TABLE 9: Model parameters and creep failure time of rock specimens with different initial damage at the creep stress level 27.4 and 29.4 MPa.

Creep stress (MPa)	Initial damage	Strain threshold (%)	E_1 (GPa)	E_2 (GPa)	η_1 (GPa-h)	η_2 (GPa-h)	Failure time (h)
27.4	D_1	0.55	9.3	80.0	3806.8	141.1	307.23
	D_2	0.49					223.85
	D_3	0.43					140.51
	D_4	0.4					98.82
29.4	D_1	0.55	8.3	63.5	2789.9	125.3	132.35
	D_2	0.49					84.92
	D_3	0.43					27.97
	D_4	0.4					4.34

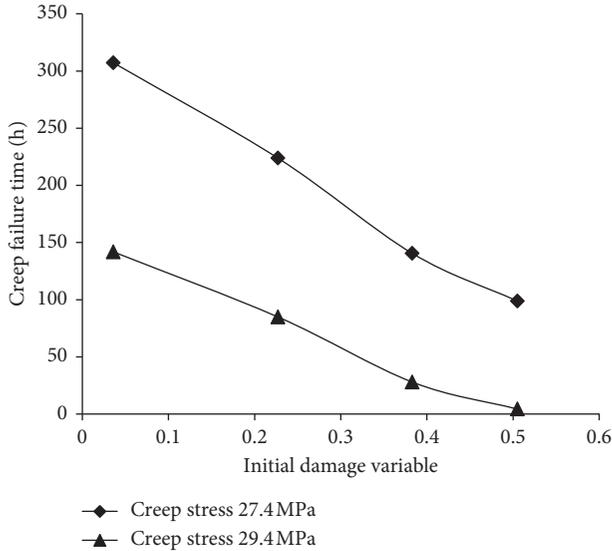


FIGURE 13: Relationship between the initial damage of rock and creep failure time.

It can be concluded that the creep failure time of rock decreases with the increase in the creep stress level. For rock engineering, the creep failure of rock is more likely to occur in the high in situ stress region.

In order to obtain the relationship between initial damage and creep failure time of rock under constant stress level, according to the evaluating method of rock failure time proposed in this paper, the creep failure time of specimens with different initial damage is predicted when the creep stress is 27.4 and 29.4 MPa, respectively. The parameters of the model and the prediction results are shown in Table 9. Based on the results, the relationship between the initial damage of rock and the creep failure time is obtained, which is shown in Figure 13. It can be seen that the initial damage of rock has a significant effect on the creep failure time, when the rock specimens are at the same creep stress level. The creep failure time of rock decreases with the increase in initial damage. For rock engineering, the rock with poor integrity is more prone to creep failure. The initial damage of the surrounding rock should be considered when predicting the service lifespan of the rock structure.

5. Conclusions

Creep tests were conducted to investigate the time-dependent behavior of sandstone with different initial damage. On

the basis of the experimental results, the LTS of rock with different initial damage was determined by four methods, and the evaluation method of creep failure time under a constant creep stress was proposed. Then, the influence of initial damage on the LTS and the creep failure time of sandstone was analyzed. The findings are summarized as follows:

- (1) Although four methods to determine the LTS of sandstone with different initial damage are given, it is found that the value of LTS cannot be obtained quantitatively by using the steady creep discriminated method, the isochronous stress-strain curve method, and the volumetric strain inflexion point determined method, which are mainly subject to the setting of the creep stress levels. However, the proposed method of identifying the intersection of axial and lateral steady creep rates can be used to quantitatively determine the LTS of rock, and it is not limited by the duration of test and the setting of creep stress levels.
- (2) The effect of initial damage on time-dependent deformation and LTS of rock is very significant. The characteristics of time-dependent deformation are related to the dilatancy threshold stress of rock; when the applied stress exceeds the stress threshold, the time-dependent deformation of rock with larger initial damage is more obvious. In addition, the relationship between the initial damage and the LTS of rock can be described by a linear function, and with the increase in the initial damage, the LTS of rock decreases.
- (3) The strain threshold corresponding to the accelerated creep is proposed as the critical index to judge the creep failure of rock, and it decreases linearly with the increase in initial damage of rock. Moreover, by combining the strain threshold of creep failure and the Burgers creep model, a model for predicting the creep failure time of rock was proposed. It is noted that the model parameters are little affected by the initial damage of rock, when the creep stress is lower than the creep failure stress.
- (4) Both the initial damage and the creep stress have a great effect on the creep failure time of rock. At the same creep stress levels, the rock with larger initial damage is more prone to creep failure. However, for rocks with similar initial damage state, the

occurrence of creep failure is related to the applied stress. The time to creep failure of rocks decreases with the increase in the creep stress levels.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

There are no conflicts of interest regarding the publication of this paper.

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