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Research Article

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Posted Date: March 23rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-348847/v1

Version of Record: A version of this preprint was published at Geotechnical and Geological Engineering on July 1st, 2021. See the published version at https://doi.org/10.1007/s10706-021-01923-8.

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Abstract: The stability of coal-rock composite structures is of great significance to coal mine safety production. To study the stability and deformation failure characteristics of the coal-rock composite structure, the uniaxial cyclic loading tests of the coal-rock composite structures with different coal-rock height ratios were carried out. Lithology and coal-rock height ratio play an important role in the energy dissipation of coal-rock composite structures. The higher the coal-rock height ratio, the greater the average elastic energy and dissipated energy produced per cycle of coal-rock composite structures, the smaller the total elastic energy and dissipated energy produced in the process of cyclic loading. Based on the difference of damage variables calculated by dissipative energy method and acoustic emission method, a more sensitive joint calculation method for calculating damage variable was proposed. The joint damage variable calculation method can more accurately and sensitively reflect the damage of coal-rock composite structure under cyclic loading. The macroscopic crack first appears in the coal specimen in the coal-rock composite structure, the degree of broken coal specimens in the composite structure is inversely proportional to the coal-rock height ratio. The strength and deformation characteristics of the coal-rock composite structure are mainly affected by coal sample in the composite structure.

Keywords: coal-rock height ratio; coal-rock composite structures; damage variable; energy characteristic; cyclic loading

1 Introduction

With the increase of coal mining depth, engineering disasters such as underground roadway deformation, roof fall and rock burst frequently occur (Maleki and Lawso 2017; Islavat et al., 2020). To ensure the safety and efficient mining of coal resources, a large number of coal pillars need to be reserved around the stope, such as isolation coal pillars, section coal pillars, waterproof coal pillars, fault protection coal pillars (Yang et al., 2019). These reserved coal pillars play the role of natural support, boundary, and isolation (Frith and Reed 2018; Wang et al. 2019). The stability of composite structure of coal pillar and roof determines the safety of the entire stope and the overlying rock. Once the composite structure of coal pillar and roof instability and damage, it will bring many catastrophic consequences, such as damage to the surface buildings, or the surface suddenly "collapses", causing heavy casualties and property losses (Mark 2018; Du et al., 2019).

The disasters in the process of coal mining are not only affected by the coal and rock themselves, but also the result of the combined action of the coal-rock composite structure. In addition to the ground stress, the coal-rock composite structure is also affected by cyclic loading of roadway driving, chamber blasting, and working face mining (Yao et al., 2020). Under this similar cyclic loading, the coal-rock composite structure will inevitably cause damage, reduce the carrying capacity, and cause the instability and destruction of roadways and coal pillars (Mathey 2018; Waclawik et al., 2018; Zhang et al., 2018).

The coal-rock composite system is accompanied by energy accumulation, transformation, and release in the process of damage and failure (Yu et al., 2020; Liu et al., 2019; Pan et al., 2020; Gao et al., 2020). Therefore, studying the characteristic of energy and damage of the coal-rock composite system under cyclic loading is of great significance to preventing coal mine disasters.

2 Analysis of the influencing factors of energy characteristics

Rock deformation and failure are accompanied by the input, accumulation, dissipation and release of energy. Analyzing the energy transformation in the process of rock deformation and failure can better find the internal essence of rock instability and failure

A large number of studies have shown that the instability and failure of the coal-rock composite structure are caused by the elastic energy accumulated by rock and coal and the work done by external forces, which can be expressed as follows (Lu et al., 2013; Li et al., 2017; Ma et al., 2020;):

$$U_u + U^e{}_r + U^e{}_c = E_c + W_c \tag{1}$$

Where U_u is the energy input from the outside, $U^e{}_r$ is the elastic energy accumulated by rock, $U^e{}_c$ is the elastic energy accumulated by coal, E_c is the total kinetic energy, W_c is the surface energy.

To reveal the energy characteristics of a coal-rock composite structure in the damage process and describe it mathematically, the loading and unloading curve of rock in a coal-rock composite structure is used to explain, there is a relationship curve as shown in Fig. 1 during the loading and unloading of the rock.

[Fig.1 here]

The area under the unloading curve is elastic energy $U^e{}_r$, and the area between the unloading curve and the loading curve is the dissipated energy $U^p{}_r$. When the rock is unloaded from strain ε_r to strain ε'_r, the elastic energy accumulated before unloading can be expressed in integral form as,

$$U_r^e = L_r S_r \int_{\varepsilon_r'}^{\varepsilon_r} \sigma \mathrm{d}\varepsilon \tag{2}$$

Similarly, the elastic energy accumulated by coal $U^e{}_c$ can be expressed as,

$$U_c^e = L_c S_c \int_{\varepsilon_c'}^{\varepsilon_c} \sigma \mathrm{d}\varepsilon \tag{3}$$

Where the L_c and L_r are the heights of coal and rock in the coal-rock composite structure; S_c and S_r are the cross-sectional areas of the coal and rock respectively; ε_r and ε_c are the strain of rock and coal body when the coal-rock composite structure reaches its peak strength, respectively; ε'_r and ε'_c are the residual strains of rock and coal respectively after rebounding.

For the unloading stage, the input energy U_u can be expressed in the integral form of the whole stress-strain curve,

$$U_u = LS \int_{\varepsilon_1'}^{\varepsilon_1} \sigma \mathrm{d}\varepsilon \tag{4}$$

Where the L and S are the overall height and cross-sectional area of the composite structure respectively, the ε'_1 is the axial strain of the whole composite structure when the peak stress is reached, it can be calculated from the overall strain recorded by the pressure machine or expressed as $\varepsilon_1' = \frac{m-n}{m}\varepsilon_r + \frac{n}{m}\varepsilon_c$, where m is the overall height of the coal-rock composite structure, n is the height of the coal body, ε_1 is the strain of the whole composite structure after the failure, which is calculated by the displacement of the pressure machine.

The total kinetic energy E_c of coal after failure can be expressed as:

$$E_\mathrm{c} = E_\mathrm{c}^1 + E_\mathrm{c}^2 = \frac{1}{2} \sum \Delta m_i v_i^2 \tag{5}$$

The surface energy W_c consumed by coal crushing can be expressed as:

$$W_c = W_\mathrm{c}^1 + W_\mathrm{c}^2 = L_c S_c C_j (r_2^{D\text{-}3} - r_1^{D\text{-}3}) \tag{6}$$

In the test, the time-strain curve $\varepsilon = g(t)$ can be obtained by a strain gauge, and there is a corresponding relationship $\sigma = \varphi(t)$ between stress and time when the load is shared by rock and coal. Therefore, there are a functional relationship $\sigma = \varphi[g^{-1}(t)]$ between strain and stress in rock and coal. There is a relationship between the height and the cross-sectional area of rock and coal:

$$\begin{cases} L = L_c + L_r = \frac{n}{m} L + \frac{m-n}{m} L \\ S = S_c = S_r \end{cases} \tag{7}$$

Therefore, formula (1) can be expressed as:

$$LS \left\{ \int_{\varepsilon_1'}^{\varepsilon_1} \sigma \mathrm{d}\varepsilon + \frac{m-n}{m} \int_{\varepsilon_r'}^{\varepsilon_r} \varphi\left[g_3^{-1}(\varepsilon)\right] \mathrm{d}\varepsilon + \frac{n}{m} \cdot \int_{\varepsilon_c'}^{\varepsilon_c} \varphi\left[g_4^{-1}(\varepsilon)\right] \mathrm{d}\varepsilon \right\} = \frac{1}{2} \sum \Delta m_i v_i^2 + \frac{n}{m} LSC_j (r_2^{D\text{-}3} - r_1^{D\text{-}3}) \tag{8}$$

Formula (8) reflects the relationship between height of rock and coal composite coal-rock composite structure and energy dissipation law: with the increase of coal height n, coal cumulative elastic $U^e{}_c$ increases, rock cumulative elastic $U^e{}_r$ decreases, and the increment of coal elastic energy is smaller than the decrease of rock elastic energy, the sum of the first three terms of the equation decreases, the surface energy term of the equation increases, the kinetic energy term decreases, the damage degree decreases, and the risk of rock burst decreases. On the contrary, the damage degree increases, the broken coal body has more kinetic energy and the risk of rock burst increases.

Besides, the properties of rock and coal also have a significant effect on energy dissipation. When the rock is used as the energy accumulator, its strength and elastic modulus affect the strain energy density. When the coal body is destroyed, the rock rapidly releases energy to aggravate the coal body failure and the risk of rock burst increases. As the main failure part of coal rock composite structure, the strength and elastic modulus of coal affect the stress-strain curve of its part.

To sum up, the damage and instability of coal-rock composite structures are mainly affected by the proportion and the mechanical properties of rock and coal. Considering the importance of stability of composite structure of coal pillar and roof, it is necessary to analyze the characteristics of the energy and damage of composite structure.

3 Test system

3.1 Test system

The experiment system is shown in Fig. 2, including the loading system, acoustic emission system, and a digital video camera. The loading system is a RAW-2000kN microcomputer-controlled electro-hydraulic servo test system. The acoustic emission system is the SH-II acoustic emission system with 16 channels, the threshold value of the preamplifier is 40dB and the resonance frequency is 150 ~ 750kHz. The digital video camera is a Canon portable digital video camera, which records the development, expansion, and failure of the coal-rock composite structure. During the test, the loading system, the acoustic emission system, and the digital video camera are synchronized to ensure the same time parameters for data processing and test analysis.

[Fig.2 here]

3.2 Specimen preparation

The coal and coarse sandstone used in the test came from the No. 3 coal seam and roof of Xin'an Coal Mine. Before the test, the coal and coarse sandstone were made into cylinders with a diameter of 50 mm and height of 100 mm, 75 mm, 67 mm, 50 mm, 33 mm, and 25 mm respectively, and the upper and lower end faces of the sample were ground with a grinding machine to meet the test requirements. The coal and coarse sandstone specimens are bonded to form coal-rock composite structures with coal-rock height ratios of 1:3, 1:2, 1:1, 2:1, and 3:1 (φ50mm×100mm). The coal-rock composite structure is marked as A, B, C, D, E according to the coal-rock height ratio from 1:3 to 3:1. The part of the specimens is shown in Fig 3.

[Fig.3 here]

3.3 Experiment scheme

The experiment adopts the stress loading method. Firstly, it is loaded at a speed of 1.5kN/s. When the load reaches 12kN (35%-45% of the uniaxial compressive strength of coal sample), unload to 2kN at the same speed, this is the first cycle. The second cycle performs loading and unloading at the same speed, but the loading peak is 2kN higher than that of the first cycle. In this way, continue loading and unloading until the specimen is destroyed. The cyclic loading and unloading curve is shown in Fig. 4.

[Fig.4 here]

4 Energy characteristic

4.1 Elastic energy

Fig. 5 shows the variation curve of elastic energy and cycles of coal-rock composite structure with different coal-rock height ratios. It can be seen that the elastic energy produced by the coal-rock composite structure increases gradually with the increase of the cycles. When the cycles are the same, the composite structure with a larger coal-rock height ratio produces more elastic energy. Because the volume proportion of coal in the composite structure with a larger coal-rock height ratio is more, the elastic strain caused by the same load is larger, and more elastic energy can be stored, the composite structure can also produce more elastic energy.

[Fig.5 here]

The average elastic energy and total elastic energy of composite structure with different coal-rock height ratios during cyclic loading are calculated. The results are shown in Fig. 6. It can be seen that the higher the coal-rock height ratio is, the greater the average elastic energy per cycle of the coal-rock composite structure is, but the lower the total elastic energy is. The smaller the coal-rock height ratio is, the smaller the average elastic energy per cycle is, but the higher the total elastic energy is. Because the composite structure with a small coal-rock height ratio has higher strength, and the average elastic energy produced in each cycle is less, but the cycles are more, which makes the accumulated total elastic energy is more; the composite structure with a large coal-rock height ratio has lower strength, and the average elastic energy produced in each cycle is more, but the cycles are less, which makes the accumulated total elastic energy is less.

The coal-rock height ratio is fitted with the average elastic energy per cycle and the total elastic energy respectively, the functional relationship between coal-rock height ratio and average elastic energy per cycle is as follows:

$$y=-0.0014x^2+0.0071x+0.026(R^2=0.78) \tag{9}$$

The functional relationship between the coal-rock height ratio and total elastic energy is as follows:

$$y=0.0079x^2-0.12x+0.55(R^2=0.99) \tag{10}$$

[Fig.6 here]

4.2 Dissipated energy

Fig.7 shows the relationship between the dissipated energy of the coal-rock composite structure with different coal-rock height ratios and the cycles. The dissipated energy of the coal-rock composite structure increases with the increase of cycles. When the cycles are the same, the higher the coal-rock height ratio is, the more dissipated energy is produced.

Because there are lots of discontinuous structures such as pores, cracks, and joints in the coal body, the distribution is extremely uneven, the cracks in the coal body develop and expand, resulting in more dissipated energy. On the other hand, there are relatively few pores, fissures, and joints in the rock, and the dissipated energy produced by cyclic loading and unloading is less. Therefore, with the increase of coal-rock height ratio, the dissipative energy of coal-rock composite structure increases.

[Fig.7 here]

The average dissipated energy per cycle and total dissipated energy of coal-rock composite structure are counted, the results are shown in Fig.8. The larger the coal-rock height ratio is, the larger the average dissipated energy per cycle is, and the lower the total dissipated energy is; the smaller the coal-rock height ratio is, the smaller the average dissipated energy per cycle is, and the higher the total dissipated energy is. Because the smaller the coal-rock height ratio, the greater the compressive strength of the composite structure, the smaller the strain produced under the same load so that the average dissipated energy produced by each cycle is less; the smaller the coal-rock height ratio is, the larger the load required for the failure of the coal-rock composite structure is, the more the cycles is, and the more total dissipated energy is.

The coal-rock height ratio is fitted with the average dissipated energy per cycle and the total dissipated energy respectively, the functional relationship between coal-rock height ratio and average dissipated energy per cycle is as follows:

$$y=-0.00152x^2+0.0072x+0.00502(R^2=0.89) \tag{11}$$

The functional relationship between the coal-rock height ratio and total dissipated energy is as follows:

$$y=-0.00822x^2+0.00688x+0.14609(R^2=0.97) \tag{12}$$

[Fig.8 here]

5 Characteristics of damage variables

5.1 Dissipated energy method

The damage and failure of rock are accompanied by energy transformation, which is an irreversible process of nonuniform dissipation. The evolution process of dissipated energy can reflect the irreversible deformation, damage, and failure characteristics of the rock. Therefore, from the perspective of dissipated energy, the evolution process of rock fatigue damage can be revealed more clearly. The damage variable D_i is defined as the ratio of the dissipated energy per cycle to the cumulative total dissipation energy, the expression is

$$D_i=U^d(i)/U \tag{13}$$

Where the D_i is the damage variable of the i-th cycle; $U^d(i)$ is the dissipated energy of the i-th cycle; the U is the cumulative total dissipated energy.

According to the dissipated energy method, the damage variables of the coal-rock composite structure under the cyclic loading are calculated, the calculation results are shown in Fig.9. It can be seen that the damage variable presents a "ladder" growth with the increase of the cycles. When the cycles are less, the damage variable is small, and the cracks in the coal-rock composite structure are compacted. With the increase of loading and cycles, the micro-cracks formed in the early stage begin to connect and form macro cracks. The micro-cracks continue to develop under the effect of cyclic loading and gradually form the second and third macro cracks. The damage variable increases greatly and forms a "ladder" growth. When the macro cracks intersect each other and develop, the composite structure becomes unstable and damaged, and the damage variable increases rapidly. The macro cracks penetrate and expand each other under the cyclic loading, which finally leads to the failure of the composite structure, and the cumulative damage variable is 1.

[Fig.9 here]

Fig.10 shows the relationship between cumulative damage variables and cycles of composite structures with different coal-rock height ratios. When the cycles are the same, the larger the coal-rock height ratio is, the greater the cumulative damage variable of the composite structure is. When the coal-rock height ratio is 1:3, 1:2, 1:1, 2:1, 3:1, the average cumulative damage variable growth per cycle is 0.0522, 0.0615, 0.0753, 0.0968, and 0.1188, respectively.

[Fig.10 here]

5.2 Acoustic emission method

The deformation and failure of the rock are not only accompanied by the outward release of energy but also generates acoustic emission signals (Zarate *et al.*, 2012; Aldahdooh *et al.*, 2013; Gu *et al.*, 2018). These acoustic emission signals contain the damage and failure information of rock materials (Moradian et al., 2016; Patricia and Celestino 2018; Zhang et al., 2019). Therefore, it is feasible to use the acoustic emission method to characterize rock damage.

It is assumed that the acoustic emission ringing number produced in the loading stages is N_{i+}, the acoustic emission ringing number produced in the unloading stages is N_{i-}, and the acoustic emission ringing number produced in each cycle is N_i, the acoustic emission ringing number when the composite structure is destroyed is N. The "i_+" means the i th loading stage, "i_-" means the i th unloading stage.

The damage variables in the loading stages and the unloading stages are D_{i+} and D_{i-} respectively; the damage variable in each cycle is D_i, and the cumulative damage variable is D, then the damage variables D_{i+} and D_{i-} produced in each loading and unloading stage can be expressed as,

$$D_{i+}=N_{i+}/N \tag{14}$$

$$D_{i-}=N_{i-}/N \tag{15}$$

The damage variable D_i generated by each cycle loading and unloading stage can be expressed as,

$$D_i=D_{i+}+D_{i-} \tag{16}$$

According to formula (1)-(3), the damage variables of composite structures with different coal-rock height ratios during cyclic loading and unloading are calculated, as shown in Fig.11. The damage variable generated in the loading stage is greater than that in the unloading stage in the whole cycle loading and unloading stages. It indicates that the fracture degree of the coal-rock composite structure is obvious in the loading stage, and the energy is released by the crack opening in the unloading stage.

[Fig.11 here]

The damage variable generated per cycle calculated by the acoustic emission method are shown in Fig.12. It can be seen that the damage is larger in the initial and later stages of cyclic loading stage, and smaller in the middle of cyclic loading stage. The relationship between the damage variable and the cycles was an approximate "*U*" shape.

In the initial stage, the damage variable decreases with the increase of cycles. The micro-cracks and micro holes in the coal-rock composite structure are gradually compacted, resulting in a large damage variable.

In the middle stage, the damage variable fluctuates with the increase of cycles, and there is no obvious decrease or increase. The internal micro-cracks of the coal-rock composite structure continue to develop, the new micro-cracks are gradually formed in the weak parts of the composite structure, the damage variable shows a fluctuating development.

In the later stage, the internal fissures expand and penetrate, the damage is aggravated, the structure gradually loses stability and damage, the damage variable increases.

[Fig.12 here]

The cumulative damage variables of coal-rock composite structures are shown in Fig.13. When the cycles is the same, the greater the coal-rock height ratio, the greater the cumulative damage variable. Because the greater the coal-rock height ratio, the lower the strength of the composite structure, the greater the deformation under the same loading, the greater the damage.

The cumulative damage variable growth rate and the average cumulative damage variable increment per cycle are shown in Fig. 10. When the coal-rock height ratio is 1:3, 1:2, 1:1, 2:1, and 3:1, the average cumulative damage variable growth per cycle is 0.046, 0.054, 0.065, 0.078 and 0.106, respectively.

[Fig.13 here]

5.3 Joint calculation method of the damage variable

The reasonable definition of damage variable should meet the following basic requirements: (1) the physical meaning is clear; (2) the measurement is convenient and convenient for engineering application; (3) the law of damage evolution is consistent with the actual deterioration process of the material; (4) the initial damage can be considered (Voyiadjis *et al.*, 2009).

At present, the calculation of damage variables is mainly based on the single parameter, such as elastic modulus, strain, dissipated energy, acoustic emission signal, etc., which has certain limitations, and there is a certain gap in the sensitivity of rock failure damage under cyclic loading. Because the process of rock failure not only releases energy but also acoustic emission signals, this information contains the internal damage information of composite structure. Therefore, the joint calculation method of damage variable is based on the dissipated energy method and the acoustic emission method to comprehensively analyze the damage variables.

Comparing the calculation results of the acoustic emission method and the dissipated energy method, the result are shown in Fig.14. In the early stage of cyclic loading, the cumulative damage variable calculated by the acoustic emission method is larger than that calculated by the dissipated energy method; while in the later stage of cyclic loading, the cumulative damage variable calculated by the dissipated energy method is larger than that calculated by the acoustic emission method. There is a certain difference in the sensitivity of the two calculation methods to the damage variables, it shows that the different calculation methods have different sensitivity to damage variables.

Therefore, the sensitivity of damage variables is analyzed by the sensitivity parameters in system analysis. When the analysis parameter a_k influences the characteristic P, let the a_k vary within its possible range, and the system characteristic P is shown as:

$$P = f\left(a_1, \ldots a_{k-1}, a_k, a_{k+1}, \ldots a_n\right) \tag{17}$$

If a small change in a_k will cause a large change in P, then P will be more sensitive to a_k; if a small change in a_k will cause a small change in P, then P will be less sensitive to a_k.

It is assumed that when the cycles are less than the $g(x)$, the cumulative damage variable calculated by the acoustic emission method is more sensitive; when the cycles are greater than the $g(x)$ value, the cumulative damage variable calculated by dissipated energy method is more sensitive. Then the joint calculation method of the damage variable is:

$$D=\begin{cases} N/N_m & n\le g(x) \\ U^d(i)/U & n>g(x) \end{cases} \tag{18}$$

Where the N/N_m is the acoustic emission method and the $U^d(i)/U$ is the dissipated energy method.

[Fig.14 here]

The $g(x)$ of composite structures with different coal-rock height ratios is shown in Fig.15. The $g(x)$ decreases gradually with the increase of the coal-rock height ratio. The relationship between the $g(x)$ and the coal-rock height ratio is fitted, and the function of the fitting curve is obtained as follows:

$$g(x)=1.08x^2-7.40x+17.97 \tag{19}$$

[Fig.15 here]

According to the joint calculation method of damage variables, the cumulative damage variables of composite structures with different coal-rock height ratios under cyclic loading and unloading are calculated, the calculated results are shown in Fig.16. It can be seen that the evolution process of cumulative damage variables generally shows a “⟋” type growth, which can be divided into three stages: in the first stage, the joints and cracks in the coal-rock composite structure and the cracks at the coal-rock interface are compacted, the cumulative damage variable increases rapidly; in the second stage, the crack propagation at the crack tip of composite structures, or the micro crack produce at the weak part of the composite structure, the cumulative damage variable increase slowly; in the third stage, after the accumulation of previous damage, the cracks in the composite structure expand and penetrate, the cumulative damage variables increase rapidly. With the increase of cycles and loading, the cracks in coal rock structure continue to expand to form the large macro cracks, and finally lead to composite structural failure, the cumulative damage variable of the coal-rock composite structure is 1. The average cumulative damage variable per cycle is 0.04764, 0.05732, 0.0698, 0.08613 and 0.12357 respectively. The calculation result is more accurate than that of the acoustic emission method and dissipated energy method.

Through the monitoring of the damage process of the coal-rock composite structure, it is found that the macro crack first appears in the coal specimen in the coal-rock composite structure and cause the axial splitting failure. The coal specimen is the first fractured body. When the coal specimen in the coal-rock composite structure is instability, the energy stored in the rock specimen will be released rapidly, which will further cause the destruction of the coal specimen in the composite structure.

The evolution law of damage variables obtained by the joint calculation method is in good agreement with the actual deterioration process of the composite structure and is more sensitive to the damage variables under cyclic loading, which can more effectively reflect the development and expansion of cracks of composite structure under cyclic loading.

[Fig.16 here]

The failure mode of the coal-rock composite structures with different coal-rock height ratios are shown in Fig.17. The coal specimens in composite structures A and B have a large degree of fragmentation and are in the form of debris. The coal specimens in the C and D structures mainly undergo splitting failure, accompanied by fragments. The coal specimens in the E composite structures mainly suffered an axial splitting failure, accompanied by external bulging of the coal wall. The rock specimen in the coal-rock composite structure did not break.

Comparing the damage degree of the coal specimen in the coal-rock composite structures, it can be found that the smaller the coal-rock height ratio, the greater the damage degree of the coal specimen in the composite structure, the smaller the volume of debris after the coal specimen is destroyed. None of the rock specimens in the coal-rock composite structure was damaged, indicating that the strength and deformation characteristics of the coal-rock composite structure are mainly affected by the strength and deformation characteristics of the weaker coal in the composite structures.

[Fig.17 here]

6 Conclusions

(1) Lithology and coal-rock height ratio play an important role in the energy dissipation of coal-rock composite structure. The higher the coal-rock height ratio, the greater the average elastic energy and dissipated energy produced per cycle, the smaller the total elastic energy and dissipated energy produced in the process of cyclic loading.

(2) The damage variable calculated by the dissipated energy method show the "ladder" growth, and the damage variable calculated by the acoustic emission method show the "U" shape. The greater the coal-rock height ratio, the greater the average cumulative damage variable growth per cycle.

(3) Based on the sensitivity of the dissipated energy method and acoustic emission method to damage variables, the more sensitive joint calculation method is proposed. The cumulative damage variable curve obtained by the joint calculation method is more sensitive and can more effectively reflect the damage and instability process of the coal-rock composite structure under cyclic loading.

(4) The macro crack first appears in the coal specimen in the coal-rock composite structure, the coal specimen is the first fractured body. The strength and deformation characteristics of the coal-rock composite structure are mainly affected by weaker coal in the composite structure. The smaller the coal-rock height ratio, the greater the damage degree of the coal specimen in the composite structure, the smaller the volume of debris after the coal specimen is destroyed.

Declarations

The authors declare they have no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

This study was supported by the National Natural Science Foundation of China [grant numbers 51604164]; and by the program of youth teacher growth plan in Shandong province.

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Figure lists

Figures

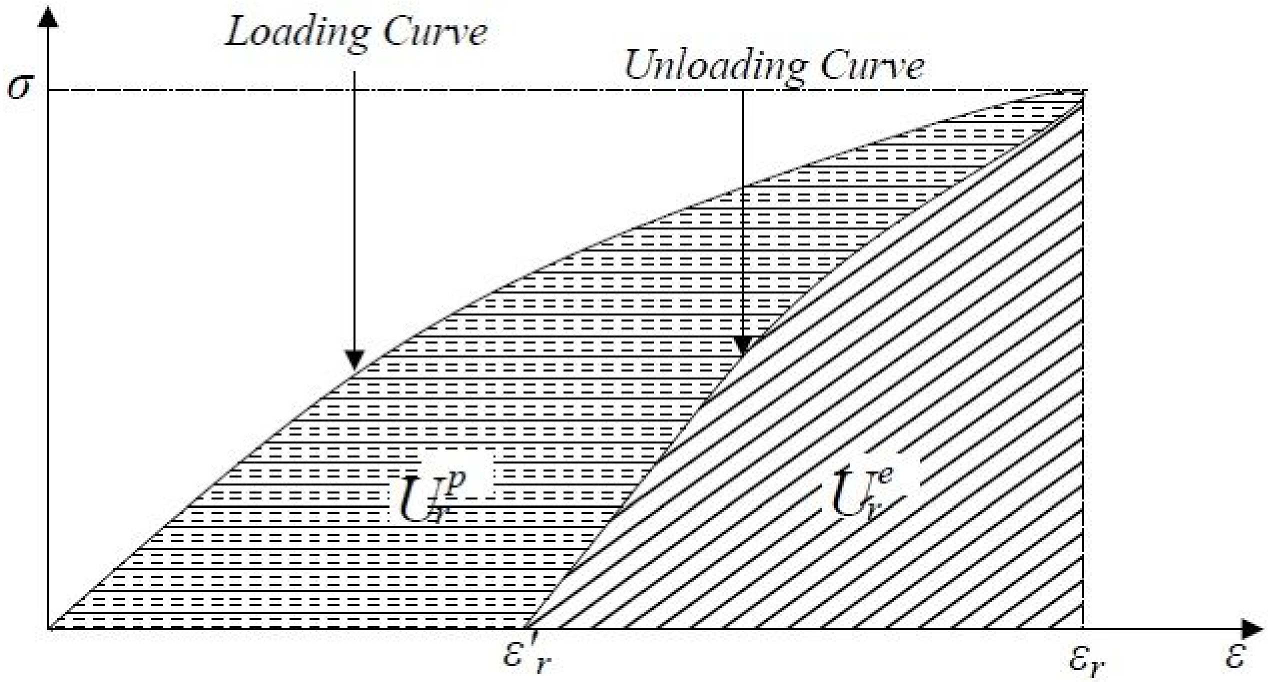


Figure 1

Loading and unloading curve

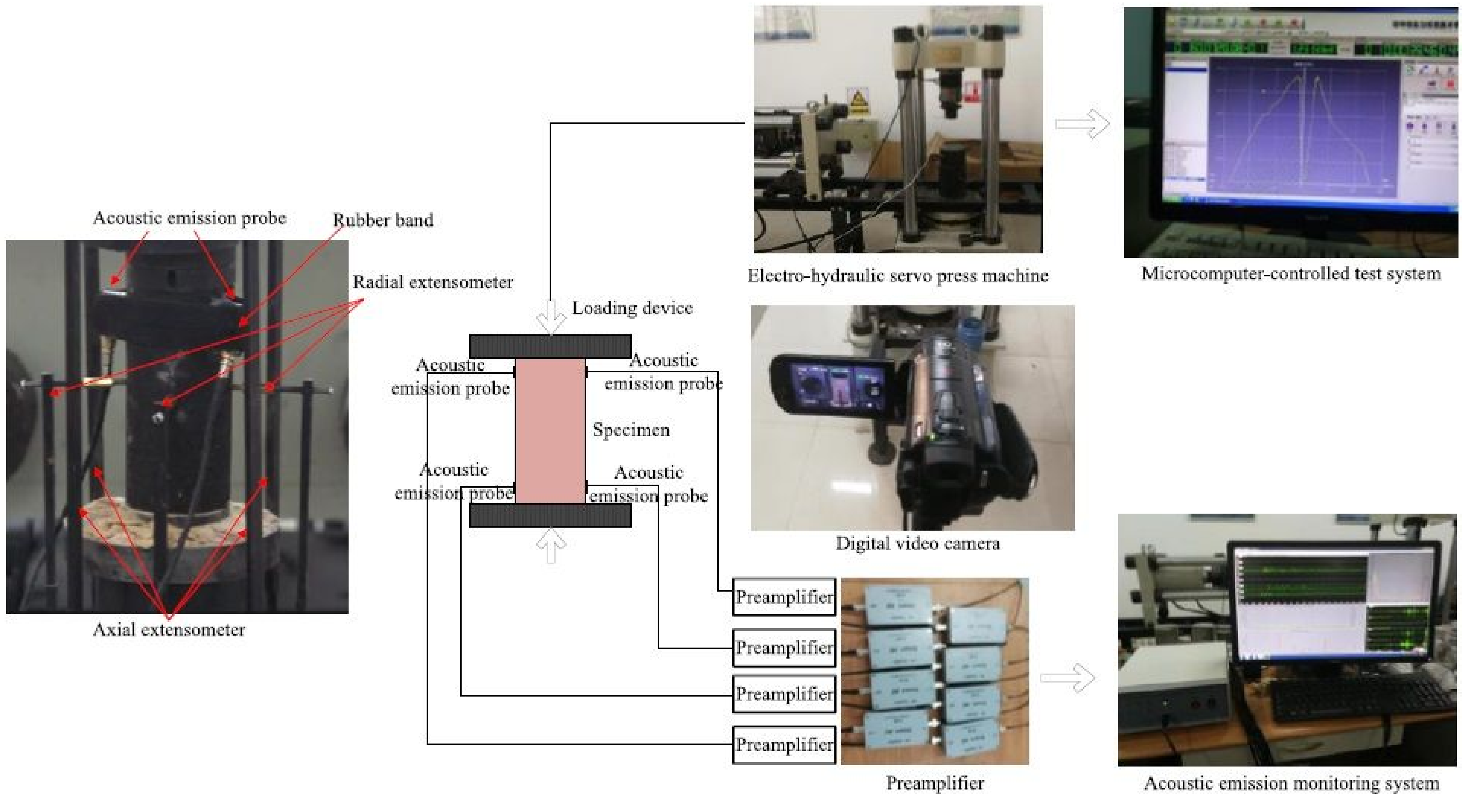


Figure 2

Test system

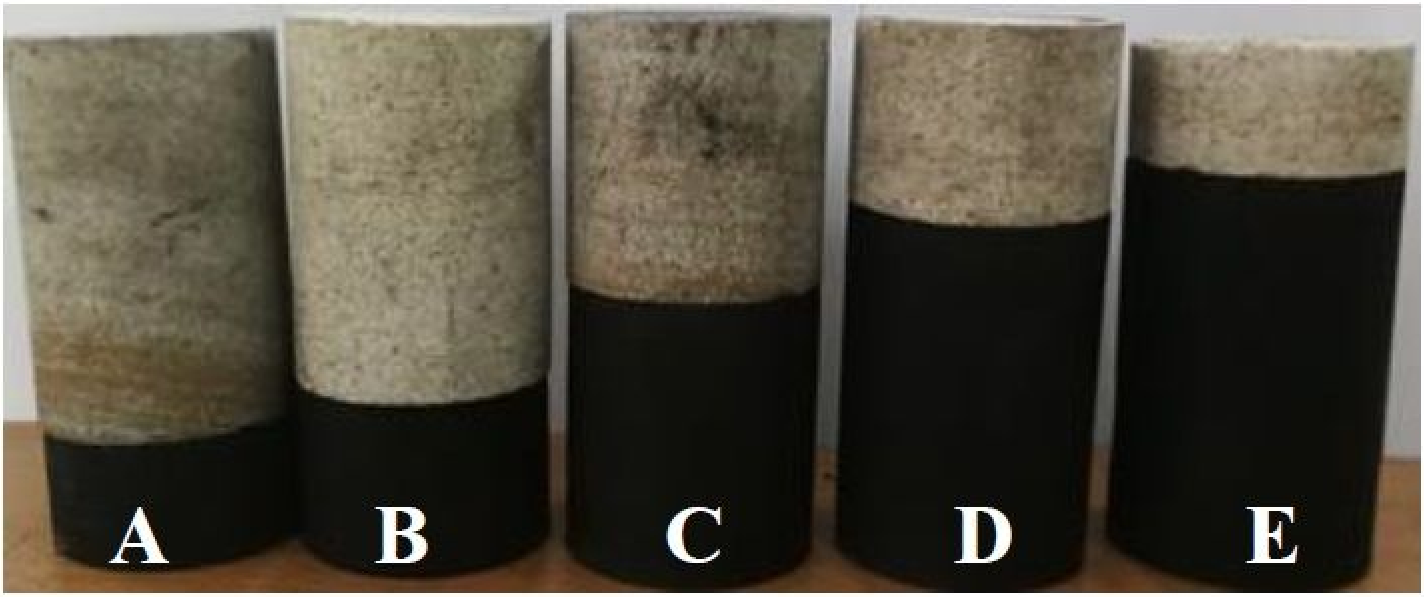


Figure 3

The part of the specimens

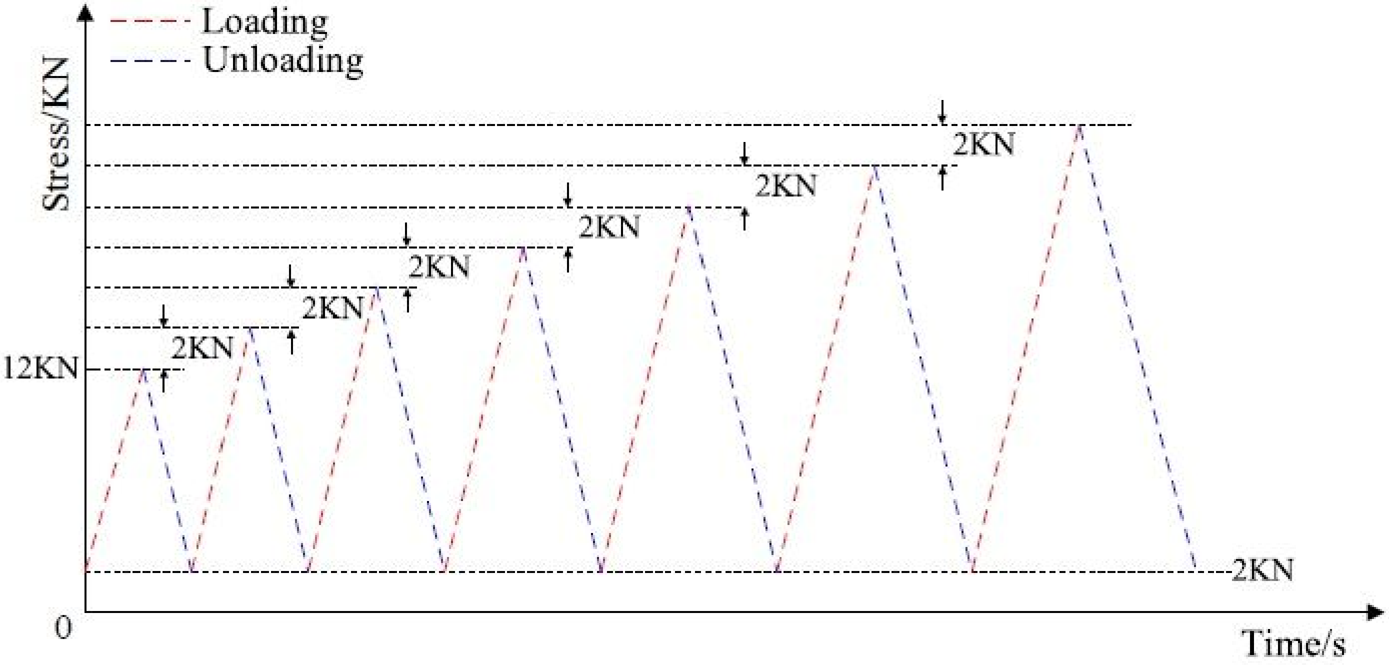


Figure 4

The cyclic loading and unloading curve

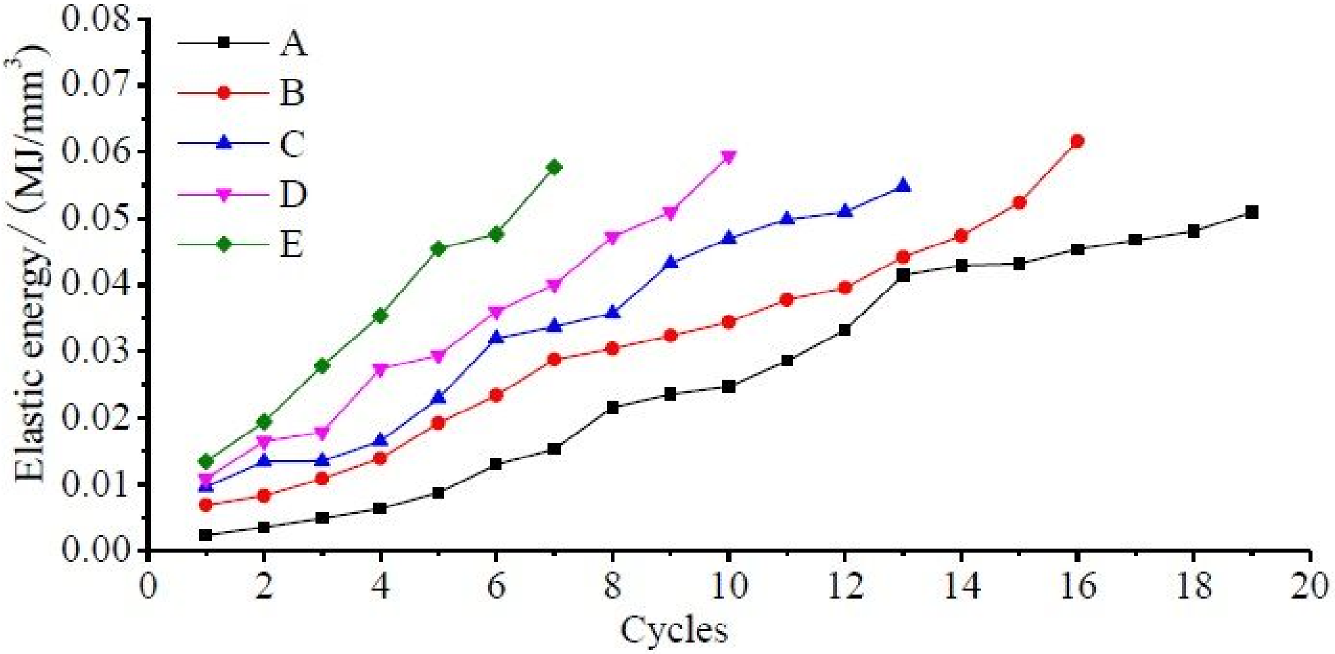


Figure 5

The variation curve of elastic energy

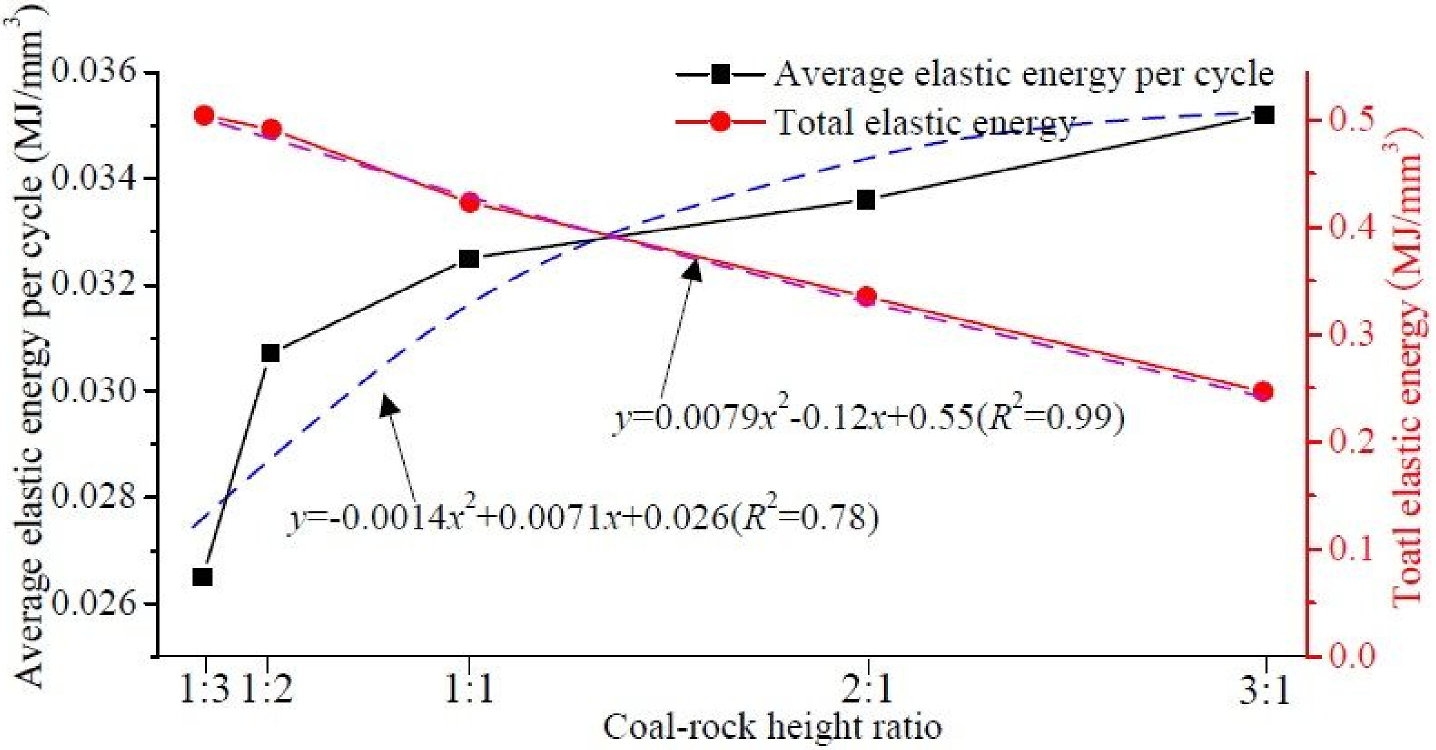


Figure 6

Variation curve of average elastic energy and total elastic energy

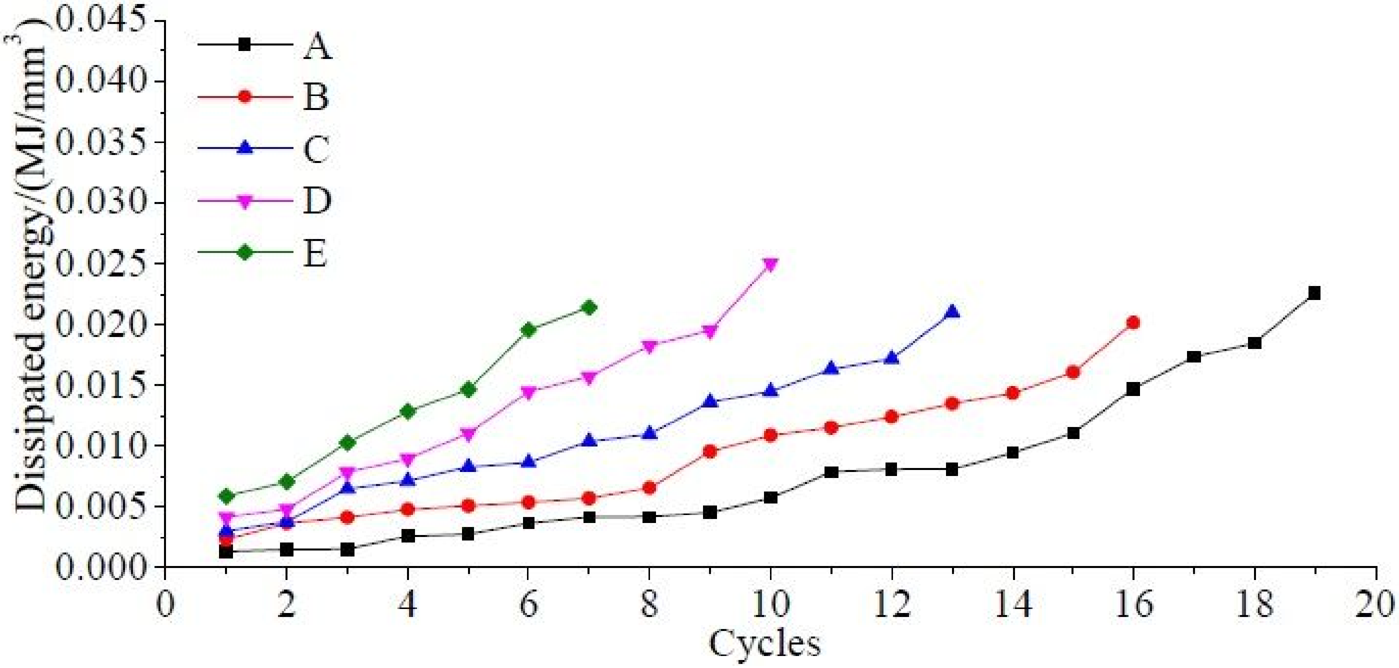


Figure 7

Variation curve of dissipated energy

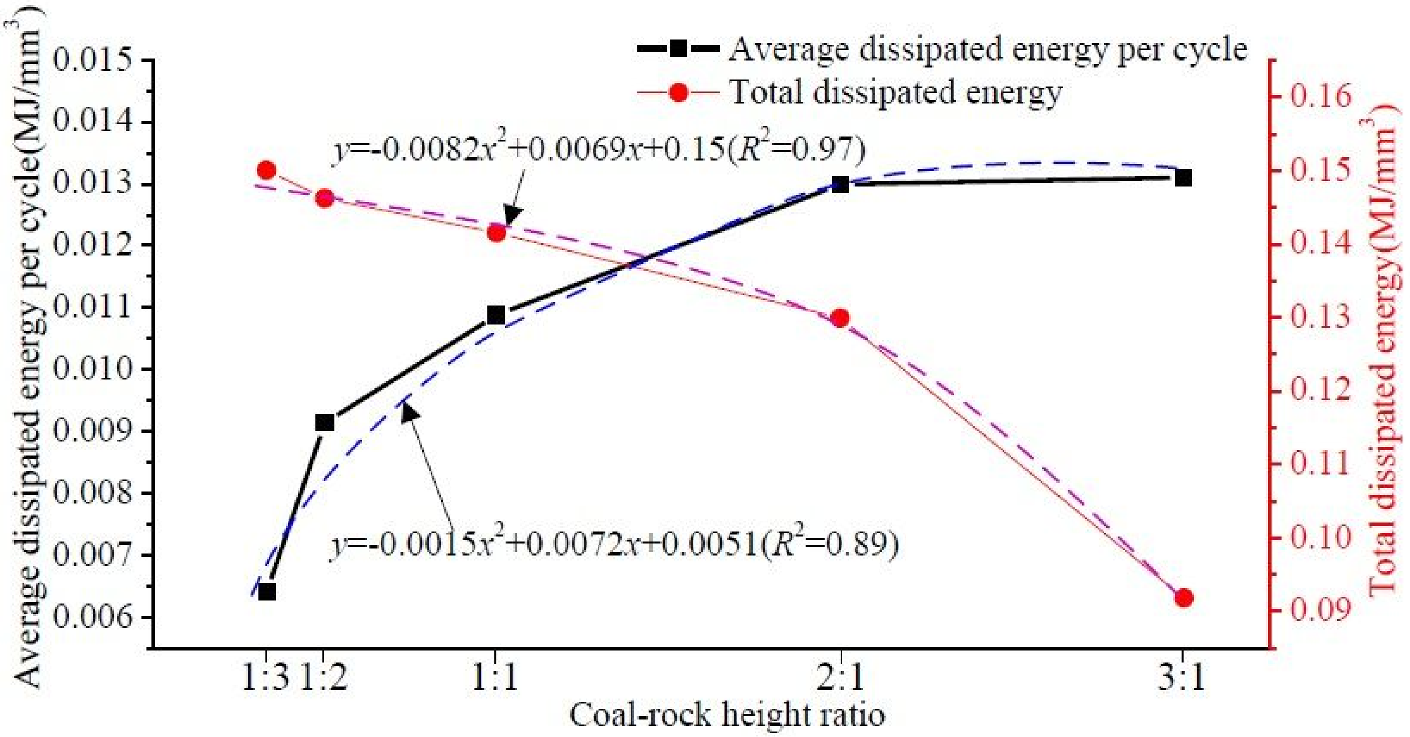


Figure 8

Variation curve of average dissipated energy and total dissipated energy

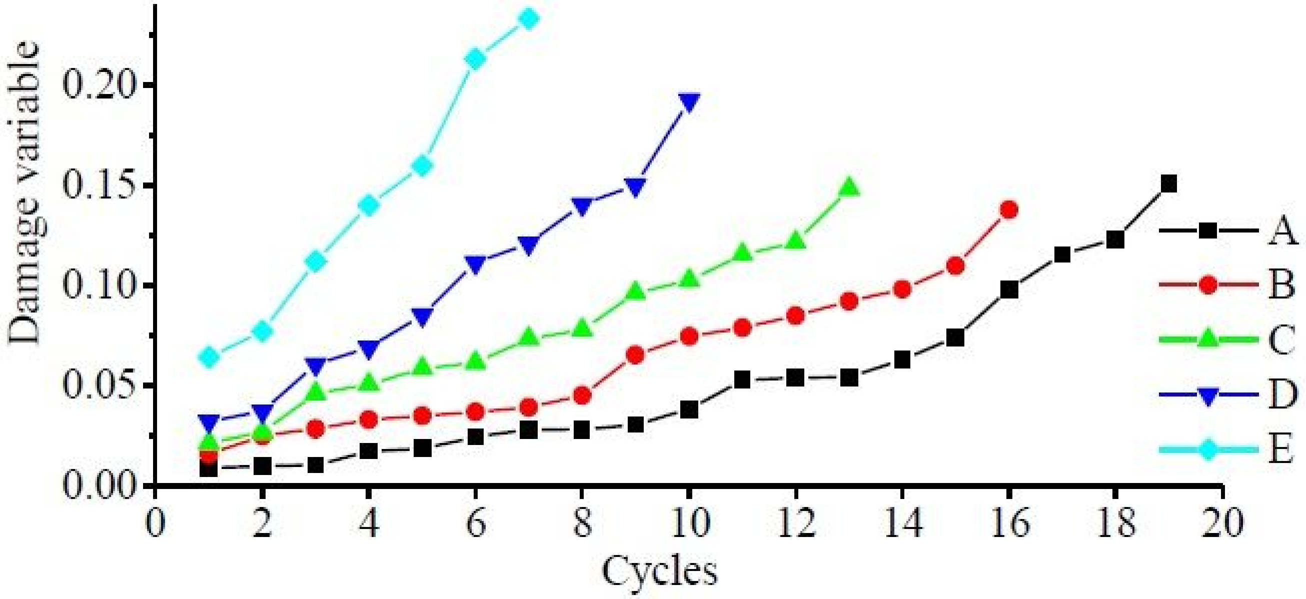


Figure 9

Variation curve of damage variable calculated by the dissipated energy method

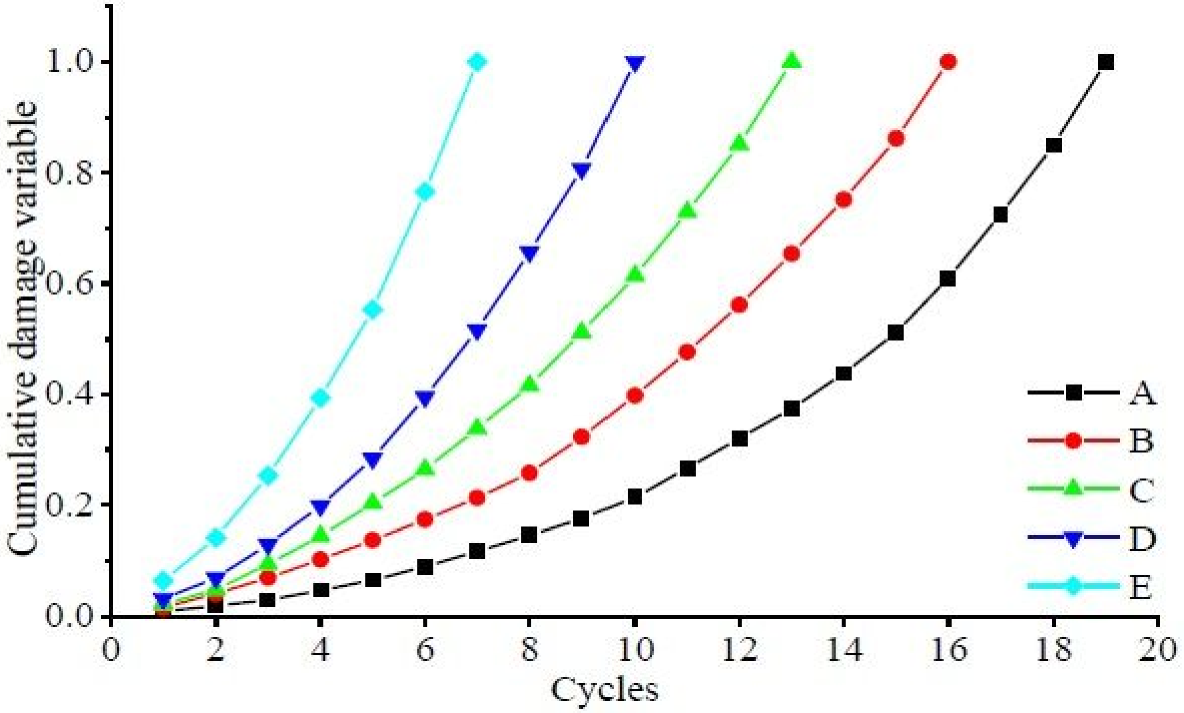
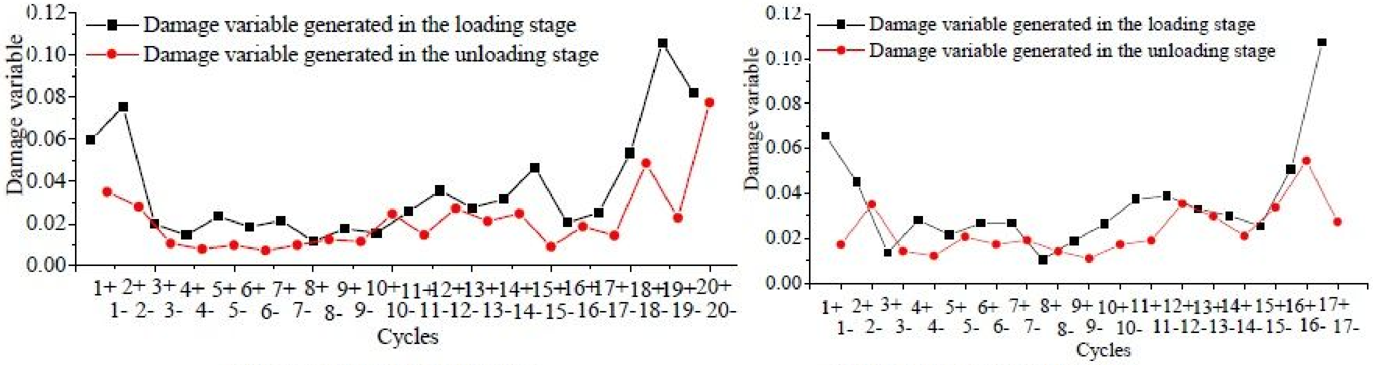
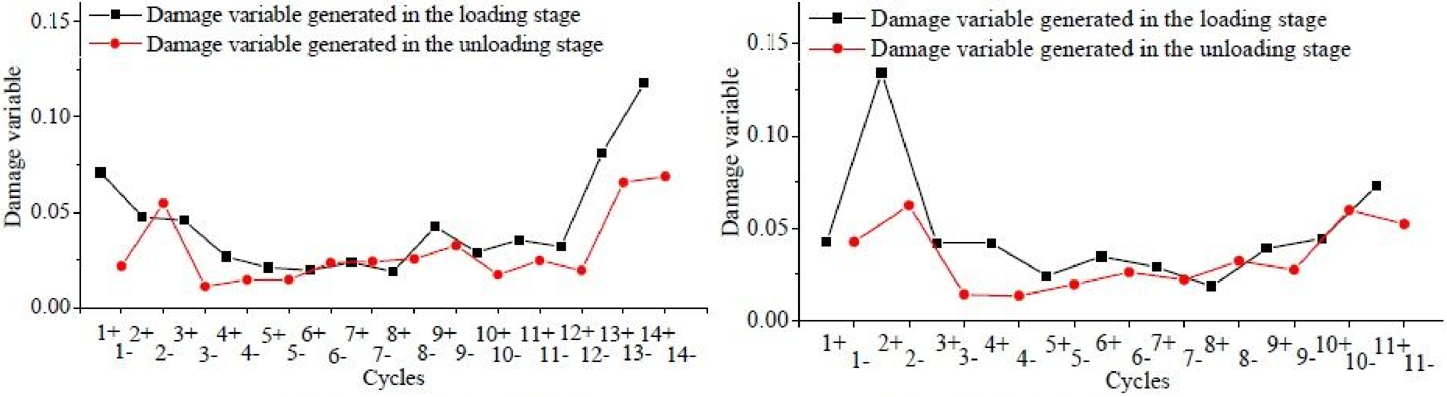


Figure 10

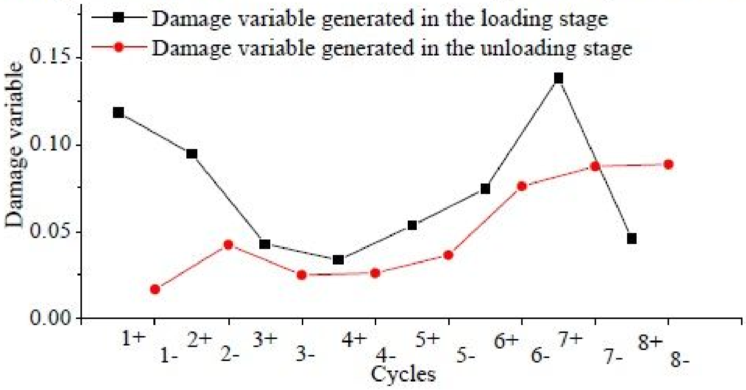
Variation curve of cumulative damage variable calculated by the dissipative energy method



(a) A composite structure (b) B composite structure



(c) C composite structure (d) D composite structure



(e) E composite structure

Figure 11

The variation curve of damage variable during cyclic loading and unloading

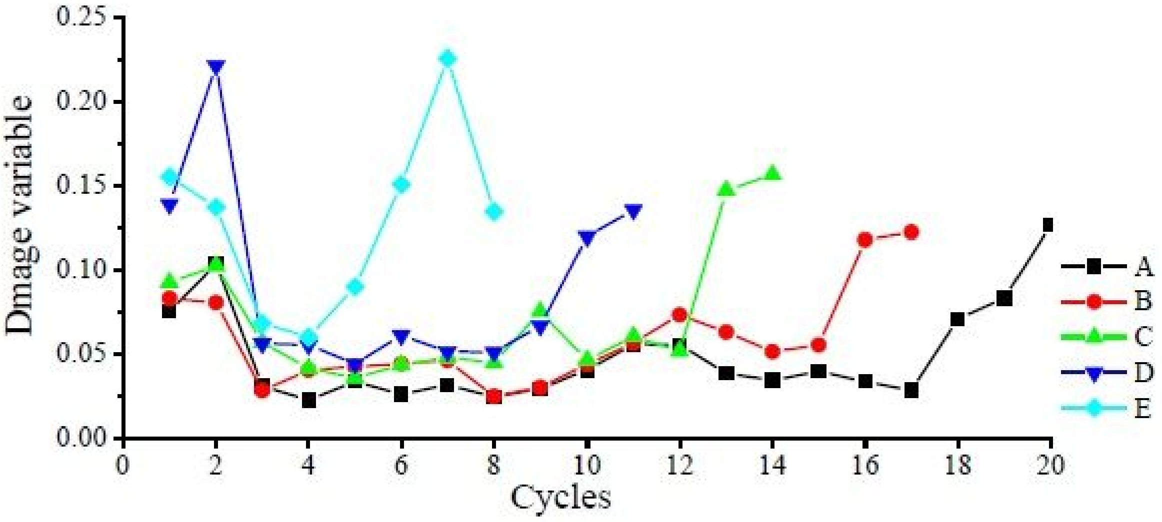


Figure 12

The variation curve of damage variables calculated by the acoustic emission method

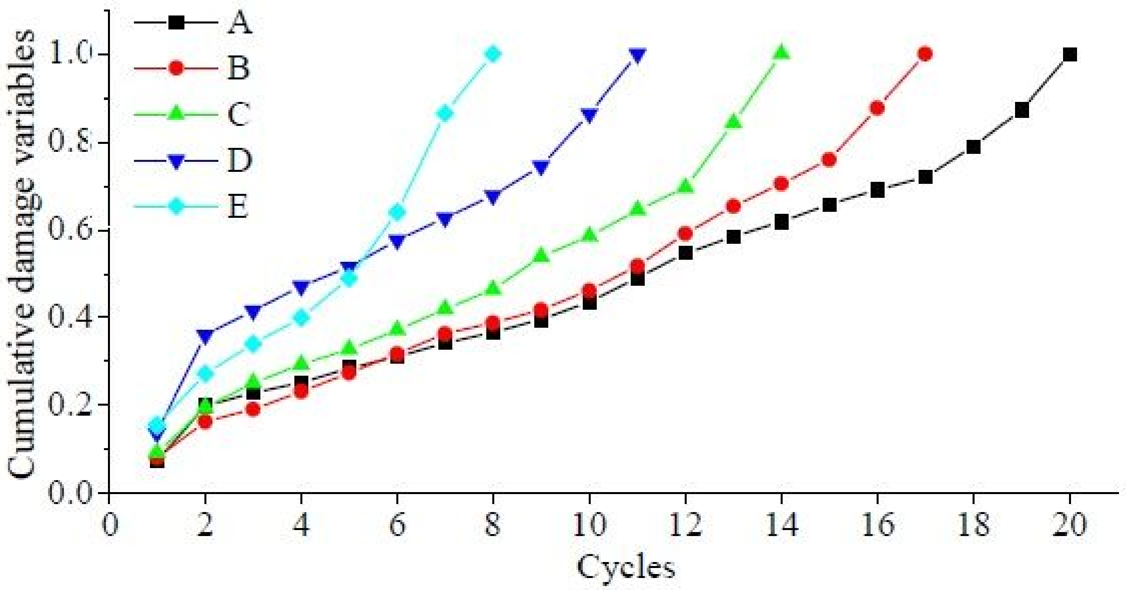
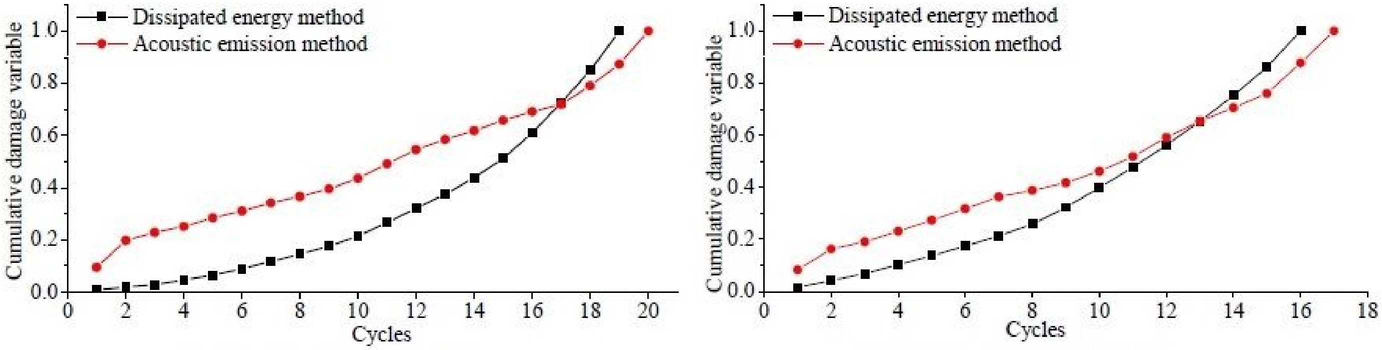
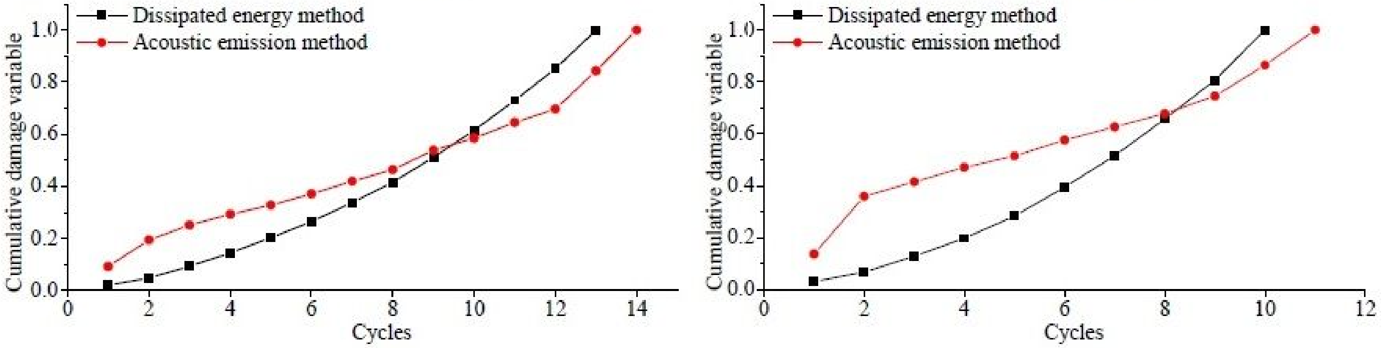


Figure 13

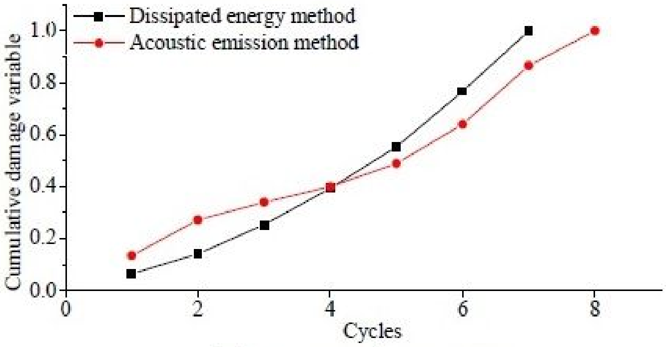
The variation curve of cumulative damage variables calculated by the acoustic emission method



(a) A composite structure (b) B composite structure



(c) C composite structure (d) D composite structure



(e) E composite structure

Figure 14

Comparison curve of dissipated energy method and acoustic emission method

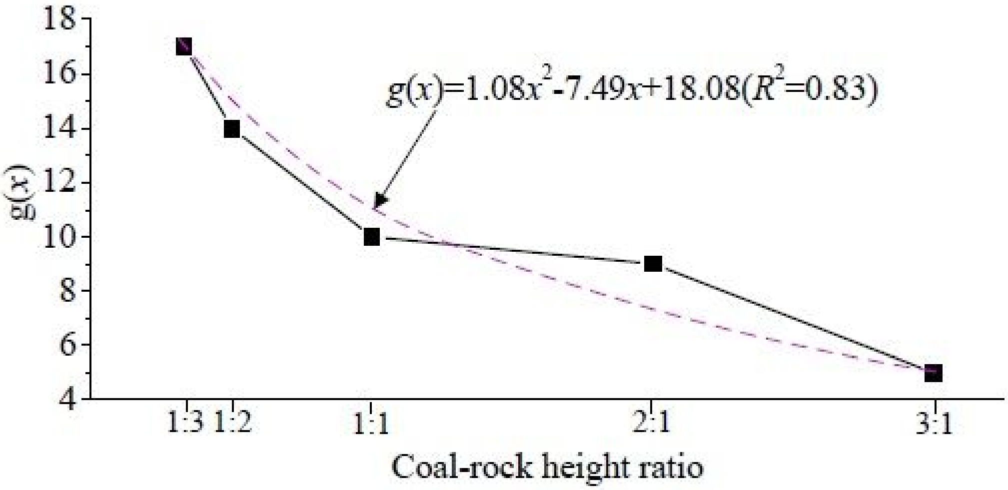
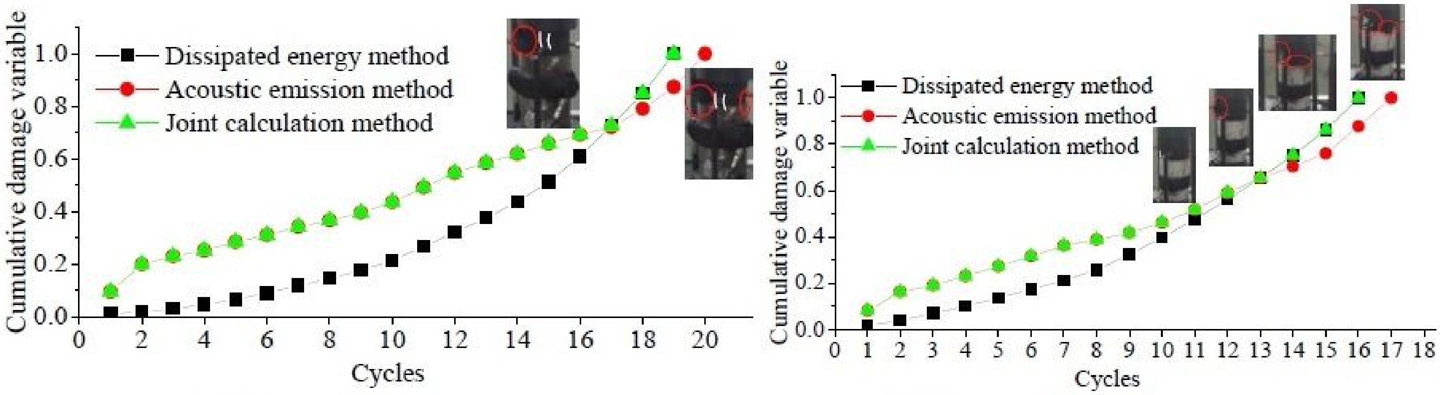
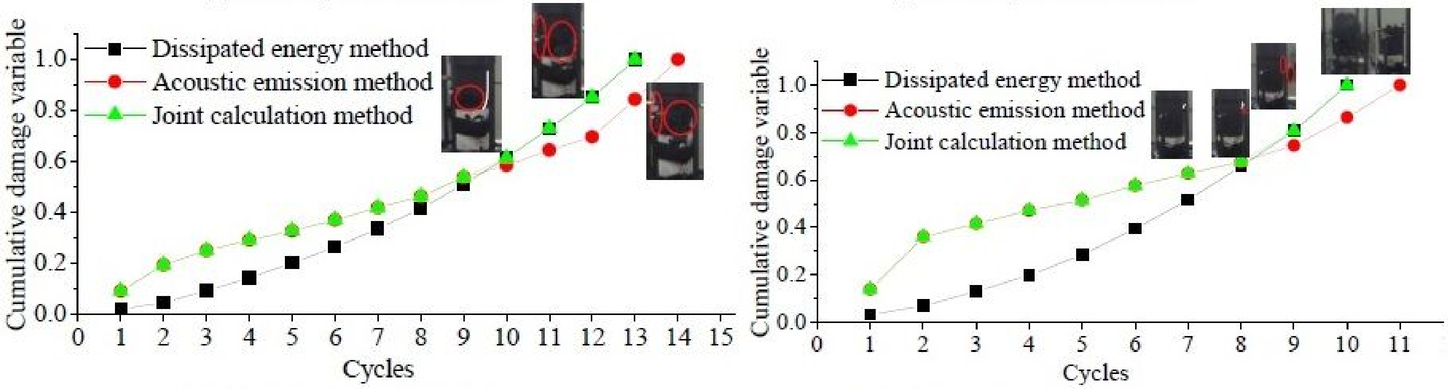


Figure 15

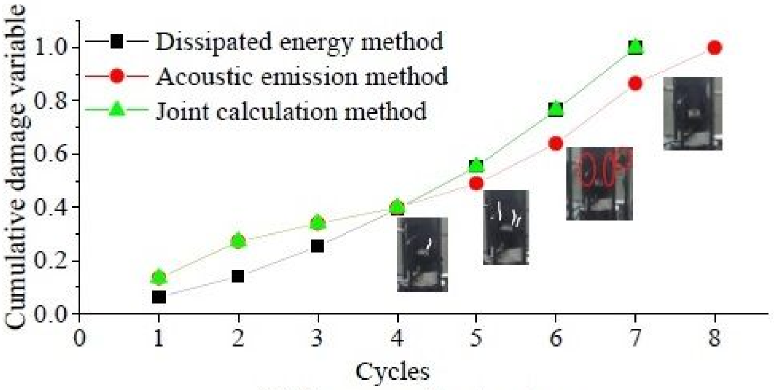
Variation curve of g(x)



(a) A composite structure (b) B composite structure



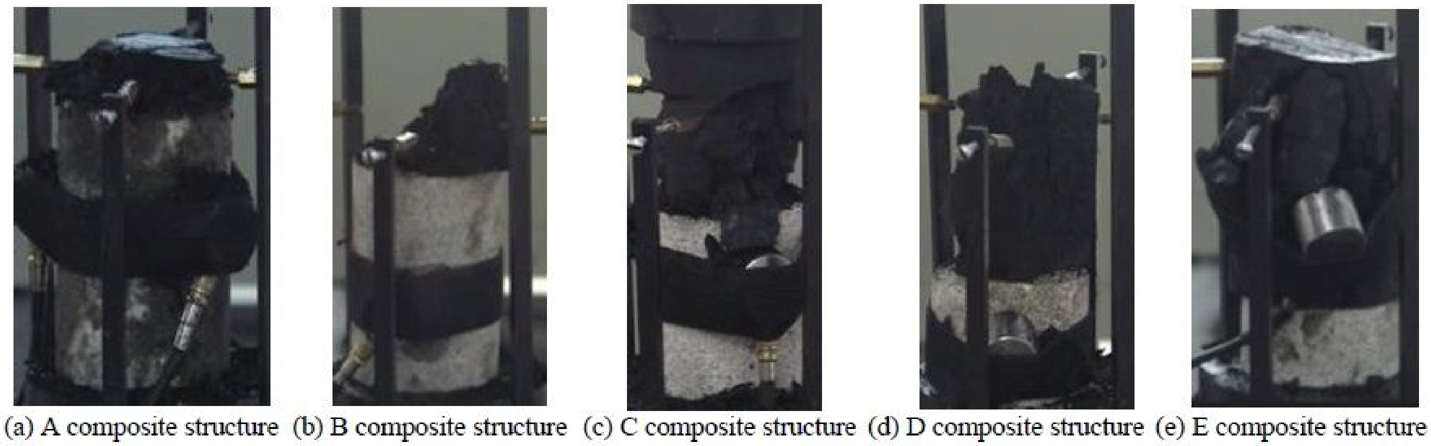
(c) C composite structure (d) D composite structure



(e) E composite structure

Figure 16

The curve of cumulative damage variable curve through the joint calculation method



(a) A composite structure (b) B composite structure (c) C composite structure (d) D composite structure (e) E composite structure

Figure 17

Failure mode of the coal-rock structural body