Journal of Engineering Science and Technology Review 9 (3) (2016) 155- 160

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Elastic Strain Energy Stored in Gas-Containing Coal Rock

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Received 28 April 2016; Accepted 22 June 2016

Abstract

The limitations of the commonly used elastic strain energy calculation method were theoretically analyzed in this study to explore the scientific method for calculating the elastic strain energy released when gas-containing coal rock was broken by considering the differences in the mechanical characteristics of hard rock and gas-containing coal rock. A novel method was proposed based on the dilatancy mechanical properties of gas-containing coal rock. The elastic strain energy of gas-containing coal rock was calculated according to the area formed by the stress–volume strain curve and the horizontal axis, with the dilatancy critical point as the boundary. The cyclic loading and unloading test for gas-containing coal rock was performed based on the rock servo gas–solid coupling test system of MTS-816. The elastic strain energy of hard rock and that of gas-containing coal rock were calculated. Results show that the common calculation method and the novel method are similar for hard rock, therefore, the scientific nature of the method proposed in this study is verified. By contrast, the calculation results of the common calculation method for the gas-containing coal rock are considerably larger than those of the novel method. The deformation characteristics of the loading process of the gas-containing coal rock are effectively reflected in the novel method because this method calculates elastic strain energy using the stress–volume strain curve. Thus, the novel method has theoretical and practical significance in the scientific prevention and control of coal mine power disasters.

Keywords: Gas-containing Coal Rock, Elastic Strain Energy, Stress–volume Strain Curve, Dilatancy Critical Point, Calculation Method

1. Introduction

The frequency and intensity of the occurrence of dynamic disasters in deep coal mines increase with the increase in mining depth. Dynamic disasters seriously threaten safe production in a coal mine. Coal and gas dynamic disasters are the comprehensive consequence of energy accumulation, dissipation, and release in the working face of a coal mine [1], [2], [3]. The energy released by coal when a coal–gas dynamic disaster occurs is mainly derived from the internal gas energy of coal and the work exerted by external forces, which is stored in the form of elastic strain energy. Energy accumulation and release from a disturbance induced by coal mining in a working face are the main causes and internal driving forces of dynamic disasters [4], [5]. Thus, an accurate grasp and prediction of energy accumulation and transformation in gas-containing coal rock are the keys to effectively prevent and control coal–gas dynamic disasters. At present, the calculation method for the elastic strain energy of coal and rock mass is based mainly on two types of energy impact tendency index. The premise of one of these indices is that plastic deformation occurs before peak stress in a coal and rock mass is disregarded beyond the negligible level. Meanwhile, the premise of the other index is that a cyclic loading and unloading test should be conducted to obtain the elastic and plastic strain energy before the loading stress of a coal and rock mass reaches its peak. The real elastic and plastic deformation energy at the peak point cannot be obtained given that the cyclic loading and unloading test can only be performed prior to the coal and rock mass peak strength and not at the peak point. A novel calculation method for the elastic strain energy of gas-containing coal rock is necessary considering the defects of the aforementioned two common energy impact index methods.

2. State of the Art

Calculation methods for the elastic strain energy of rocks without gas rock were more than those for gas-containing coal rocks [6], [7], [8], [9], [10]. The classical rock energy impact index method was widely used. Goodman proposed the energy impact index. The area formed by the full stress–strain curve and the horizontal axis was divided into two parts using the energy impact index method with the ultimate strength of the coal and rock mass as the boundary. The left and right sides represent elastic strain energy (W_e), which was stored during the loading process, and plastic strain energy (W_p), which was consumed through destruction [11], [12], [13], [14]. Kidybinski, a Polish researcher, proposed that the elastic strain energy index (W_{et}) of a rock could be used as the rock burst tendency index. The stress loading on a rock specimen was first loaded into 0.7 or 0.8 times R_b when the uniaxial compression strength (R_b) test was performed and then unloaded into 0.05 R_b. The strain energy released at the time of unloading was the elastic

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ISSN: 1791-2377

strain energy stored in the rock, whereas the strain energy lost was the plastic strain energy [15], [16], [17]. Domestic and foreign scholars have conducted relevant research on the elastic strain energy calculation method based on the aforementioned two classical rock energy impact indices. Xie studied the intrinsic relations among energy dissipation, energy release, strength, and abrupt structural failure of rocks during the failure process, and then defined the concept of the elastic strain energy release of a rock unit [21]. Li analyzed the energy accumulation and release principle in the process of rock failure based on the water content effect of the evolution law of rock energy consumption; the calculation method for elastic strain energy was defined through uniaxial and conventional three-axis compression tests [22]. Guo studied the evaluation method for elastic strain energy rock burst tendency and then defined the calculation method for elastic strain energy. The aforementioned studies mainly focused on calculating the elastic strain energy of rocks without gas [23]. The calculation idea was not changed. The elastic strain energy was only obtained by disregarding the plastic strain before the peak strength of the rock or the cyclic loading and unloading test at peak strength. The calculation method for elastic strain energy stored in gas-containing coal rock has not yet been reported both locally and abroad because of the considerable difference in the mechanical deformation characteristics of hard rock without gas and gas-containing coal rock. Research on the calculation method for the elastic strain energy of gas-containing coal rock has theoretical and practical significance in the scientific prevention and control of coal mine power disasters.

The rest of this paper is organized as follows. Section 2 describes the research status of the calculation method for the elastic strain energy of coal and rock masses. Section 3 proposes the novel method, in which the elastic strain energy of gas-containing coal rock is calculated according to the stress–volume strain curve with the dilatancy critical point as the boundary. Section 4 calculates the elastic strain energy of hard rock and gas-containing coal rock using the novel method and the impact tendency index method. Section 5 presents the conclusions of the study.

3. Methodology

3.1 Elastic Strain Energy Calculation Method for “Stress–Volumetric Strain”

Damage in coal and rock masses causes macroscopic instability during energy drive. Consequently, coal and rock mass dynamic disasters will occur. Therefore, accurately grasping and forecasting the process of energy accumulation and transformation in coal and rock masses is the key to effectively controlling coal and gas dynamic disasters. Calculating elastic strain energy accurately is critical to prevent and control coal and gas dynamic disasters.

The deformation and breaking of coal and rock masses involve the processes of energy input, elastic energy accumulation, energy dissipation, and energy release. In the processes of energy dissipation and elastic strain energy storage of coal and rock masses, the following formula must be satisfied if no energy exchange occurs between the coal and rock mass and the external environment [18], [19], [20].

$$U = U^d + U^e \tag{1}$$

Where U is the total energy from the external force, U^d is the dissipation energy (the change is irreversible), and U^e is the elastic strain energy stored in the coal and rock mass.

In the stress–strain curve of i units in a coal and rock mass (Fig. 1), the U_i^d area indicates the plastic deformation energy of the unit, whereas the U_i^e area indicates the elastic strain energy stored in unit.

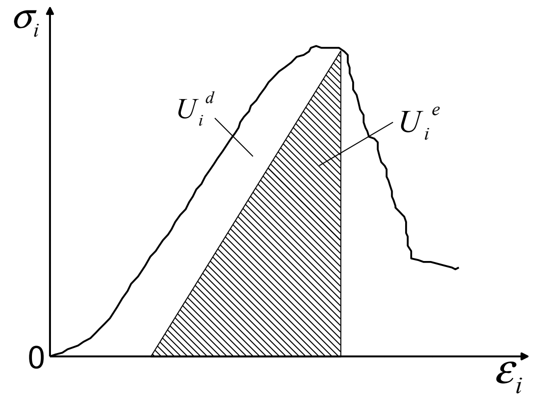

Fig.1. Relationship between elastic strain energy and dissipated energy in a coal and rock mass unit

The total energy and elastic strain energy of each part of the coal and rock mass unit can be expressed as [22], [23]

$$U = \int \sigma_1 d\varepsilon_1 + \int \sigma_2 d\varepsilon_2 + \int \sigma_3 d\varepsilon_3 \tag{2}$$

$$U^e = \frac{1}{2}\sigma_1\varepsilon_1{}^e + \frac{1}{2}\sigma_2\varepsilon_2{}^e + \frac{1}{2}\sigma_3\varepsilon_3{}^e \tag{3}$$

$$\varepsilon^e = \frac{1}{E_i}\left[\sigma_i - \mu_i\left(\sigma_j + \sigma_k\right)\right] \tag{4}$$

Where σ_i , σ_j , σ_k (i, j, k = 1,2,3) represent the principal stress; ε_i denotes the strain; ε_i^e indicates the elastic strain in the direction of the principal stress; μ_i is the Poisson’s ratio; and E_i is the unloading elastic modulus.

In summary, elastic strain (ε_i^e) was the key to calculating the elastic strain energy when a coal and rock mass was loaded. The successful division of the elastic deformation and plastic deformation of a gas-containing coal rock was the precondition to obtain elastic strain.

Research shows that gas-containing coal rock exhibits dilatancy mechanical behavior before reaching peak intensity [25], [26], [27]. The properties and definition of dilatancy mechanics indicate that the volume of gas-containing coal rock was expanded prior to reaching peak intensity instead of being compressed as it was before. Along with such expansion, the inner fracture was extended, which increases damage on the coal and rock mass.

Therefore, plastic deformation dominates the dilatancy process until the destruction of the gas-containing coal rock. The critical stress value of dilatancy decreases with the increase in the gas pressure of coal in the gas-containing coal rock under the influence of gas. The area of this section increases during dilatancy and during the destruction of the gas-containing coal rock, which indicates an increase in plastic deformation. The value of elastic strain energy will be overcalculated if the plastic deformation energy was disregarded and mistaken as the elastic strain energy. Thus, the driving force that produces dynamic disasters increases in the gas-containing coal rock, and the prediction of coal and gas dynamic disasters becomes erroneous.

Accordingly, a novel method for calculating the elastic strain energy via the volumetric strain curve was proposed in this study by considering the mechanical characteristics of gas-containing coal rock. The area between the volume strain curve of the compression section and the horizontal axis was regarded as the elastic strain energy of the coal and rock mass given that the critical point of dilatancy of the gas-containing coal rock was the boundary. The elastic deformation and plastic deformation of the gas-containing coal rock were successfully distinguished using this method, and the calculation error of the elastic strain energy caused by disregarding plastic deformation can be solved.

Figure 2 shows that compression precedes expansion when the gas-containing coal rock was loaded during the dilatancy deformation process. Strain deformation was mainly plastic deformation after dilatancy. Thus, the elastic strain energy with the dilatancy critical point (point A) of the coal and rock mass as the boundary can be calculated via the area between the volume strain curve (0–A segment) and the horizontal axis. This area was shown as S_{OAB} in Fig. 2, and its stored elastic deformation energy (W_e) is

$$W_e = \int_0^{\varepsilon_B} \sigma_i d\varepsilon_v \tag{5}$$

Where ε_v is the volume strain value, ε_B is the corresponding strain value at the dilatancy critical point, and σ_i is the stress.

Volumetric strain was calculated through the axial strain and the transverse strain as follows:

$$\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \tag{6}$$

Where $\varepsilon_2 = \varepsilon_3$. Formula (6) is

$$\varepsilon_v = \varepsilon_1 + 2\varepsilon_2 \tag{7}$$

Where ε_v is the volume strain value, ε_1 is the axial strain value, and ε_2 and ε_3 are the transverse strain.

An analysis of Fig. 2 shows that the shaded area S_{OAB} was the area of the curved edge triangle. Thus, the area was calculated using the definite integral method. The curved edge shape was divided into small units, and each unit can be approximated to a small rectangle. The sum of the area of all the small rectangles was the curved edge triangle area. Thus, the actual calculation can be performed according to Formula (8) as follows:

$$W_e = \sum \sigma_i \varepsilon_{\Delta vi} \tag{8}$$

Where $\varepsilon_{\Delta vi}$ is the corresponding unit volume strain value of σ_i, and σ_i is the stress.

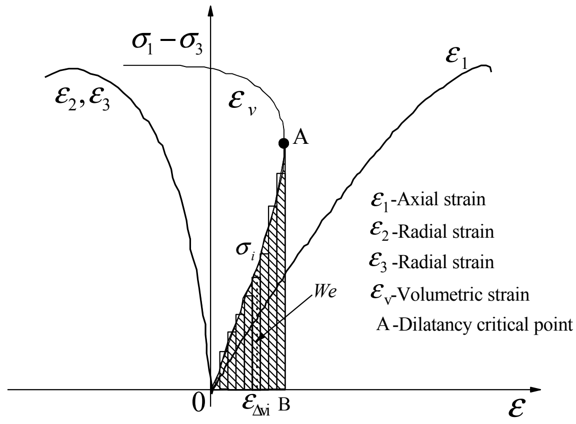

Fig.2. Stress–strain curve of the gas-containing coal rock

3.2 Experimental Equipment and Sample

The cyclic loading and unloading experiment on the gas-containing coal rock was conducted based on the rock servo gas–solid coupling test system of MTS-816 type (Figs. 3 and 4). The test sample came from no. 6 coal obtained from the Xieqiao Coal Mine in Huainan. The marble exhibited rock burst tendency. The sample was processed into a ϕ 50 mm × 100 mm cylinder following the international standard.

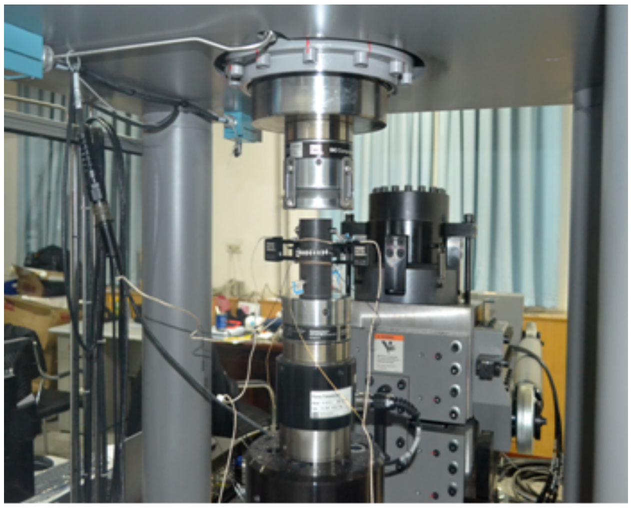

Fig.3. MTS-816 testing system

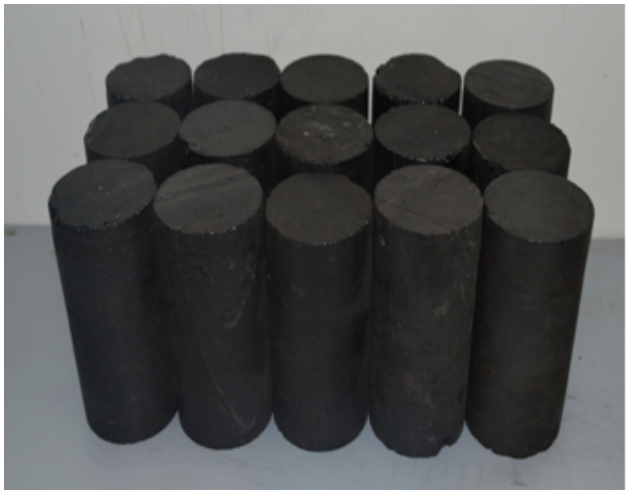

Fig.4. Standard coal sample

4 Result Analysis and Discussion

4.1 Experimental Result Analysis

4.1.1 Analysis of the Experimental Result from Hard Rock

Marble with rock burst tendency was selected to calculate the energy and verify the results (Fig. 5).

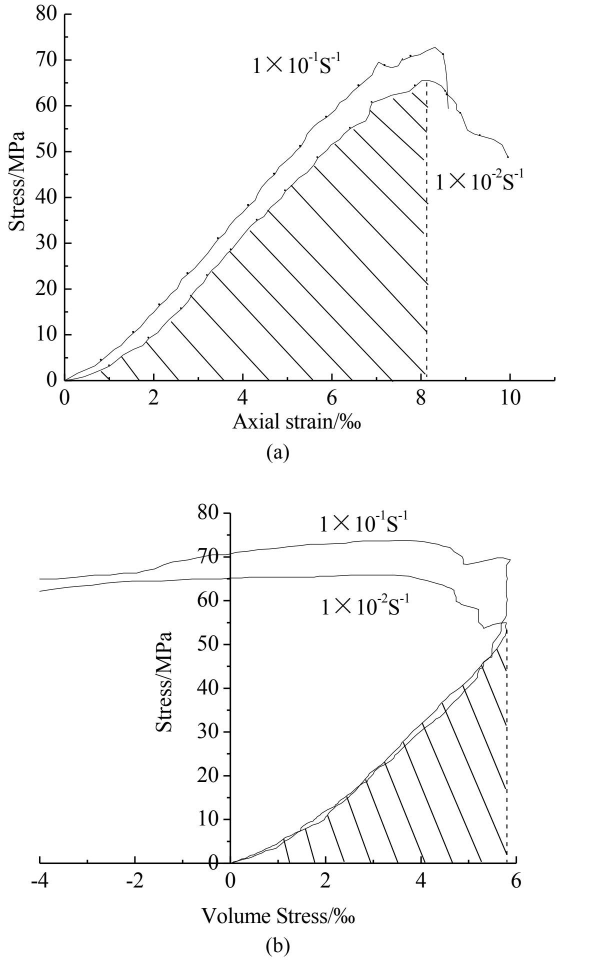

Fig.5. Stress–strain curve of marble. (a) Stress–axial strain (b) Stress–volume strain

The stress–axial strain curve and the stress–volume strain curve were used to calculate the elastic strain energy under loading strain rates of $1\times10^{-1}S^{-1}$ and $1\times10^{-2}S^{-1}$, respectively. The result was presented in Table 1.

Table 1. Result of the stress–strain curve elastic strain energy for marble

Lithology	Elastic strain energy before peak value (J)	Actual stored elastic strain energy $*W_{e0}$ (J)	Elastic strain energy We (J) (novel calculation method)
Marble 1	260.92	130.46	124.95
Marble 2	291.64	145.82	139.55

Note: The actual stored elastic strain energy was calculated using the elastic strain energy index method. The index value is 2.

Table 1 shows that the elastic strain energy stored in marble was 130.46 J and 145.82 J when the loading rate was $1\times10^{-1}S^{-1}$ and $1\times10^{-2}S^{-1}$, respectively, using the energy index method. Meanwhile, the calculation results were 124.95 J and 139.55 J, respectively, using the stress–volume strain curve with the dilatancy critical point as the boundary. The two calculation results were similar, and the error rate was approximately 4.22%. Thus, using this novel method to calculate elastic strain energy was scientific and reasonable.

4.1.2 Analysis of the Experimental Result from Coal Mass

The cyclic loading and unloading stress–strain curve of the coal mass was shown in Fig. 6. The unloading stress–strain curve of the coal mass was not coincident with the original loading curve in the processes of cyclic loading and unloading. Thus, plastic deformation occurs in coal before peak intensity. Coal mass was a porous heterogeneous medium unlike hard rock. Plastic deformation replaces elastic deformation as the major deformation state before the stress value reaches the peak. The calculated value of the elastic strain energy storage must be higher than the true value if the deformation before the peak intensity approximates the elastic deformation. Thus, the accuracy and reliability of predicting dynamic disasters of coal mass was significantly reduced.

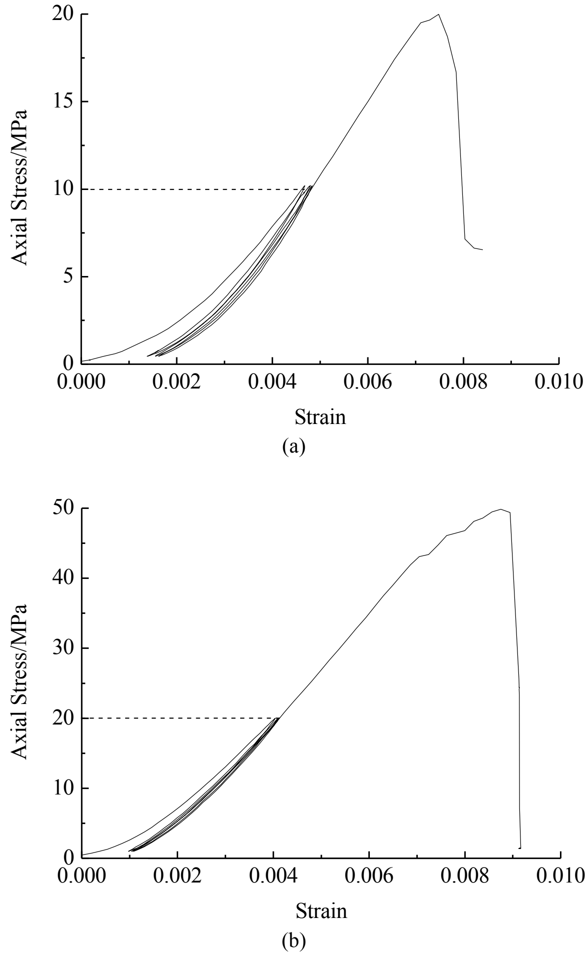

Fig.6. Axial stress–strain curve of the cyclic loading of gas-containing coal rock. (a) 10MPa (b) 20MPa

4.1.3 Analysis of the Experimental Result from Gas-Containing Coal Rock

An experimental study on the mechanical properties of gas-containing coal rock based on the rock servo gas–solid coupling test system of MTS-816 type was conducted under different initial gas pressure values. The initial gas pressure was 1, 2, and 3 MPa for gas-containing coal rock. The stress–axial strain and stress–volume strain curve from the test were shown in Fig. 7. The calculation results of the elastic strain energy were presented in Table2.

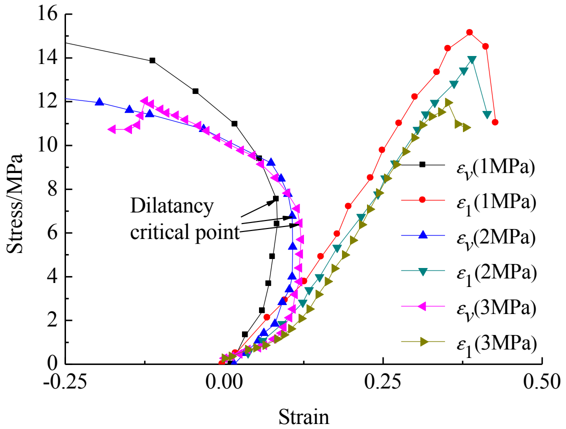

Fig.7. Gas-containing coal rock stress–strain curve under different initial gas pressure values

Table 2. Result of the stress–strain curve elastic strain energy for marble

Gas pressure (MPa)	Elastic strain energy before peak stress (J)	Elastic strain energy of volumetric strain curve (J)
1	357.19	26.90
2	243.39	23.28
3	179.94	14.87

Table 2 shows that the elastic strain energy stored in the coal mass was 357.19, 243.39, and 179.94 J when the gas-containing coal rock was loaded and the energy index method was used. Meanwhile, the results were 26.90, 23.28, and 14.87 J when calculated using the stress–volume strain curve with the dilatancy critical point as the boundary. The results indicate that the elastic strain energy calculation value using the common index method was higher than the result using the novel calculation method of the stress–volume strain curve. Thus, the physical and mechanical properties of the gas-containing coal rock change because of the gas effect. The main deformation state shifts from elastic deformation to plastic deformation before peak stress was reached in the gas-containing coal rock compared with the dense rocks. The elastic strain energy stored decreases significantly, whereas its gas expansion energy increases rapidly with gas pressure increase. Consequently, the risk of a dynamic disaster increases considerably. The calculation results must be in great discord with the real amount of elastic strain energy stored inside if plastic deformation was disregarded when calculating elastic strain energy, and plastic strain energy was merely regarded as part of the latter. This practice is incomprehensive and unreasonable and may lead to undesirable consequences in coal and gas dynamic disaster forecast.

4.2 Experimental Discussion

In the energy impact index method, the elastic strain energy was calculated using the area value formed by the stress–axial strain curve and the horizontal axis before the peak intensity of the coal and rock mass was reached. Both elastic deformation and plastic deformation occur in the coal and rock mass before the load reaches the peak intensity, and thus, their energy should not be calculated separately. Otherwise, the energy loss from plastic deformation was disregarded, thereby resulting in a larger value than that in reality. The loading and unloading rebound curve (Fig. 6) in the elastic strain energy index method should be used to calculate elastic strain energy. This curve can only be produced during the loading and unloading test, and can only be conducted before the peak intensity (approximately 70% or 80%) was reached but not at the peak point. Therefore, the value of the elastic strain energy obtained using this method was inaccurate. The novel calculation method for elastic strain energy was based on the stress–volume strain curve of the coal and rock mass with complete consideration of the 3D axial–radial deformation. The actual deformation state of the coal and rock mass under stress was better reflected using this method. The dilatancy critical point of the coal and rock mass was selected as the boundary in calculating elastic strain energy. Plastic deformation was considered the major deformation form after the coal and rock mass dilates. Thus, elastic deformation and plastic deformation are successfully distinguished.

This study shows that the results of the hard rocks were similar when using the common calculation method and the novel method based on the stress–volume strain curve with the dilatancy critical point as the boundary in the loading process. Moreover, the elastic strain energy can be accurately obtained using both methods. By contrast, for the gas-containing coal rock, the novel method can better reflect the deformation characteristics in the loading process, whereas the common method fails. Thus, the novel method can effectively overcome the inaccuracy problem.

5 Conclusion

The elastic strain energy stored in stressed gas-containing coal rock was studied based on theoretical and experimental analyses to explore the scientific calculation of the elastic strain energy released when a gas-containing coal rock was broken. The main conclusions drawn are as follows.

(1) A novel method was proposed. The elastic strain energy of gas-containing coal rock was calculated according to the stress–volume strain curve with the dilatancy critical point as the boundary. The elastic strain energy of gas–solid coupled coal and rock mass could be calculated using this method.

(2) The novel calculation method for elastic strain energy fully considered 3D axial–radial deformation. The range of elastic deformation and plastic deformation were effectively distinguished. The actual deformation state of gas-containing coal rock under stress could be effectively reflected using this method.

(3) The elastic strain energy of hard rock and that of gas-containing coal rock were calculated. The research showed that the results of the common calculation method and those of the novel method were similar for hard rock. Thus, the scientific nature of the new method was verified. However, the calculation results of the common method for the gas-containing coal rock were considerably larger than those of the novel method. Thus, the novel method is more suitable for calculating the elastic strain energy of loading gas-containing coal rock.

The accurate calculation of the elastic strain energy of gas-containing coal rock can realize the scientific prevention and control of coal mine power disasters. The method proposed in this study suggests further research on the mechanical characteristics and the influencing factors of the dilatancy of gas-containing coal rock.

Acknowledgements

This work was supported by the Natural science research project of University of Anhui Province (NO. KJ2015A048), the National Natural Science Foundation of China (NO.

51304007), Anhui Provincial Natural Science Foundation (1408085MKL42).

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