

## *Retraction*

# **Retracted: Study on Mechanical Characteristics of Energy-Absorbing and Anti-Scour Bolts**

### **Complexity**

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This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

- (1) Discrepancies in scope
- (2) Discrepancies in the description of the research reported
- (3) Discrepancies between the availability of data and the research described
- (4) Inappropriate citations
- (5) Incoherent, meaningless and/or irrelevant content included in the article
- (6) Manipulated or compromised peer review

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

### **References**

- [1] Z. Tang, H. Wu, J. Lv, Z. Xin, and W. Zuo, "Study on Mechanical Characteristics of Energy-Absorbing and Anti-Scour Bolts," *Complexity*, vol. 2021, Article ID 8876517, 9 pages, 2021.

## Research Article

# Study on Mechanical Characteristics of Energy-Absorbing and Anti-Scour Bolts

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In order to improve the impact resistance and mechanical performance of anchor rods and satisfy the requirements for supporting rockburst roadways, the energy balance equation of the energy-absorbing support and roadway surrounding rock system is established. Moreover, to effectively prevent rockburst disasters, the energy criterion for roadway instability is derived. From the perspective of an energy-absorbing support, a yield-absorbing anti-shock anchor composed of a rod body, tray, constant resistance energy-absorbing device, and special-shaped nut is designed and developed; compared with ordinary anchor rods, this rod has stronger mechanical properties for resisting impact. Theoretical and numerical simulation studies show that the energy-absorbing device has a repeatable deformation failure mode and a constant yield force. The paper also presents the principle involved in the design of anti-shock bolt supports. The energy-absorbing support not only effectively guides and controls the release and conversion of impact energy but also consumes the impact energy in the buffering process of the anchor to ensure the stability of surrounding rock and support protection system. This study aims to provide reference for roadway support design and to improve rock bolts used in rockburst roadways.

## 1. Introduction

The current energy system requires coal to further perform its function as “ballast stone.” Coal is therefore anticipated to continue as China’s leading energy source in the future. The continuous large-scale exploitation of resources in previous decades, however, has exhausted the country’s shallow coal resources. Future exploitations of coal resources are expected to reach depths of 1000–2000 m. At depths beyond 1000 m, the geological conditions of coal resources become more complex, the original rock stress increases, the surrounding rock deformation of roadways becomes severe, and ground pressure impact becomes the primary threat leading to disaster in many mining areas [1–5]. In Poland, from 1949 to 1982, a total of 3097 large-scale destructive shocks occurred, causing 401 deaths and damaging 1, 20, 000 m of wells and roads. From 1910 to 1978, the Ruhr Coal Mine in Germany experienced 283 large-scale destructive shocks [6], and from 1933 to 2019, China experienced 9020

destructive coal mine rockbursts [7]. It is predicted that as mining depths increase, rockburst and its resulting series of accidents will increasingly become severe, extremely retarding the exploitation of deep coal resources. The control of surrounding rock of deep roadways is one of the key problems in deep mining theory. In coal mining, the inadequacy of roadway support is the main problem encountered in roadway surrounding rock control as well as rockburst prevention and control.

For rockburst roadway support, a new type of suction bolt with a constant working resistance and good elongation capacity has been developed [8–11]. In reality, suction bolts have been studied by scholars from various countries for over 20 years. In the early 1990s, Ortlepp [12] proposed the concept of an energy-absorbing support system, and Jager [13] developed the first true suction bolt—the cone bolt. It was not until the late 1990s that resin-anchored tapered bolts were introduced [14]. In recent years, having gained in-depth knowledge on energy-

absorbing bolt and supports, experts have developed a variety of supports such as Garford anchor, Durabar anchor, yielding Secura anchor, Roofex anchor, and anchor conceived by Varden et al. [15–17]. With the focus set on the actual surrounding rock deformation of coal mine roadway sustaining ground pressure impact, the negative Poisson's ratio material of the anchor rod (cable) is investigated, and a high constant resistance large deformation anchor cable is designed. Most existing anchor rods are not designed based on attaining strong impact resistance; consequently, they are weak against impact. From the perspective of impact resistant design, most investigations focus on the research and development of new materials and new types of support members. Although the application of these research results has resulted in certain headways, it has also considerably increased the cost of roadway support. In view of the limitations of existing bolts and the dearth of special requirements for tunnel support in sustaining ground pressure impact, a new type of energy-absorbing anti-scour bolt is designed and developed. In order to provide reference for the design and improvement of rock bolt support in rockburst roadway, the structure composition and working principle of this new bolt are investigated.

The specific contributions of this paper include the following:

- (1) The energy balance equation of the energy-absorbing support and roadway surrounding rock system is established based on the principle of energy conservation.
- (2) The energy criterion for the instability of roadway supported by an energy-absorbing system is deduced. Accordingly, the foregoing provides a theoretical basis for energy-absorbing support and anti-scour design.
- (3) This paper presents the principle involved in energy absorption and anti-scour.
- (4) In view of the advantages afforded by energy-absorbing supports, a type of energy-absorbing anti-scour bolt, composed of rod body, tray, constant resistance energy-absorbing device, and special nut, is designed and developed. The test results indicate that the energy-absorbing anti-scour bolt has stronger impact mechanical properties than the ordinary bolt.

The rest of this paper is organized as follows. In Section 2, the energy balance equation of the energy-absorbing support and roadway surrounding rock system is established based on the principle of energy conservation. Moreover, the energy criterion for the instability of roadway supported by an energy-absorbing system is deduced. A type of energy-absorbing anti-scour bolt, composed of rod body, tray, constant resistance energy-absorbing device, and special nut, is designed in Section 3. Section 4 shows the simulation experimental results, and Section 5 concludes the paper with summary.

## 2. Energy Criterion for Instability of Roadway

Rockburst is defined as the sudden and instantaneous release of energy from the coal and rock mass around the roadway. This energy mainly emanates from a source and is transmitted to the roadway in addition to the energy accumulated through the elastic deformation of roadway surrounding rock.

The initial energy of an earthquake (as impact source) is reduced by the propagation of waves through the surrounding rock until the roadway surrounding rock is reached. Let it be assumed that the initial energy of the rockburst source is  $E_z$ , the radius of the circular roadway is  $r$ , the distance from the rockburst source to the center of the roadway is  $d$ , and the energy attenuation index of the rockburst shock wave propagating through the coal rock medium is  $\eta$ . With the foregoing, the energy ( $E_{zh}$ ) released from the impact ground pressure of the impact source is calculated as follows:

$$E_{zh} = E_z (d - r)^{-\eta}. \quad (1)$$

The elastic deformation energy of the roadway surrounding rock that has accumulated in the original rock stress field is expressed by the following equation:

$$E_3 = \iiint_V \left[ \frac{[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)]}{2E} \right] dx dy dz. \quad (2)$$

Upon the initiation of roadway surrounding rock failure, the stress state of the coal rock mass rapidly changes from a three-way to a two-way force and then immediately transforms to a one-way force. According to the minimum energy principle for energy transfer, the energy required for coal rock mass failure is the failure energy under unidirectional stress, i.e., the minimum failure energy ( $E_{\min}$ ).

$$E_{\min} = \frac{\sigma_c^2}{2E}, \quad (3)$$

$$\text{or } E_{\min} = \frac{\tau_c^2}{2G}.$$

In the roadway excavation process, various forms of energy dissipation (e.g., plastic deformation of rock mass, relative joint plane slippage in surrounding rock mass, viscous flow deformation, secondary crack, and crack propagation at the crack tip of surrounding rock mass) occur. If it is presumed that the right side of the equation is  $E_q$ , then the rockburst energy ( $E_p$ ) derived from the elastic deformation energy of the surrounding rock is as follows:

$$E_p = E_3 - E_{\min} - E_q. \quad (4)$$

According to equations (1) and (4), the energy released from coal and roadway surrounding rock mass is obtained when rockburst occurs.

$$E_{cj} = E_{zh} + E_p = E_z (d - r)^{-\eta} + E_3 - E_{\min} - E_q. \quad (5)$$

When rockburst occurs, a part of the energy released by the coal rock mass around the roadway is absorbed by the roadway support structure, and the other part is released to the roadway in the form of coal rock kinetic energy.

If it is assumed that  $\delta$  denotes the maximum deformation of the roadway supporting structure, which can withstand an impact load,  $F_{zf}$ , under the surrounding rock pressure, then the energy absorbed by the elastic deformation of the roadway supporting structure can be calculated as follows:

$$E_{zf} = \frac{\delta F_{zf}}{2}. \quad (6)$$

If it is assumed that the energy released to the roadway in the form of coal rock kinetic energy is  $E_k$  when rockburst occurs, then according to the law of conservation of energy,

$$E_{cj} = E_{zf} + E_k. \quad (7)$$

That is,

$$E_z(d-r)^{-\eta} + E_3 - E_{\min} - E_q = \frac{\delta F_{zf}}{2} + E_k. \quad (8)$$

To prevent the roadway from impacting the ground pressure, the energy ( $E_k$ ) that should be released to the roadway in the form of coal rock kinetic energy must be equal to zero. If  $E_k$  is greater than zero, then

$$E_z(d-r)^{-\eta} + E_3 - E_{\min} - E_q > \frac{\delta F_{zf}}{2}. \quad (9)$$

The foregoing shows that the roadway support structure cannot fully absorb the energy released by rockburst, and the residual energy ( $E_k$ ) will be released to the roadway in the form of coal rock kinetic energy, resulting in the damage of the support structure and collapse of the surrounding rock. Equation (9) is therefore the energy criterion for roadway impact failure.

If it is assumed that the support has an energy absorption function and the energy absorbed by the energy-absorbing device is  $E_x$ , then according to equation (8), the energy conservation equation for energy absorption and roadway anti-scour support is expressed as follows:

$$E_z(d-r)^{-\eta} + E_3 - E_{\min} - E_q = \frac{\delta F_{zf}}{2} + E_x + E_r + E_k. \quad (10)$$

If the energy ( $E_{cj}$ ) released by rockburst is greater than the energy ( $E_x$ ) absorbed by the energy-absorbing device and the energy ( $F_{zf}$ ) absorbed by the elastic deformation of the support structure, then

$$E_{cj} = E_z(d-r)^{-\eta} + E_3 - E_{\min} - E_q > E_x + E_r + E_{zf}. \quad (11)$$

This shows that the support cannot completely absorb the impact pressure to release energy, and the remaining energy ( $E_k$ ) is either projected as kinetic energy or transformed into a large displacement of the surrounding rock to free space; this causes support damage and collapse of the roadway surrounding rock. Equation (11) is therefore the

energy criterion for the instability of roadway supported by an energy-absorbing system.

According to the foregoing criterion, the adoption of an energy-absorbing support in the roadway can considerably enhance the anti-impact performance of the support system as well as effectively preclude and control the occurrence of rockburst. Ultimately, the criterion provides a theoretical basis for the anti-impact design of an energy-absorbing bolt support.

### 3. Design of Energy-Absorbing Anti-Impact Anchor

**3.1. Structural Design of Energy-Absorbing Anti-Impact Anchor.** The incorporation of a constant resistance energy-absorbing device to the conventional anchor rod is adopted for the design of the energy-absorbing anti-scour anchor rod shown in Figure 1. This rod includes four parts: rod body (1), tray (2), constant resistance energy-absorbing device (3), and special-shaped nut (4). The right end of the rod body is fabricated with external threads that can be connected to the nut, and the center of the tray has a mounting hole for the rod body. The constant resistance energy-absorbing device, which has a 150–200 mm thin-walled circular tube structure, is placed between the tray and special-shaped nut. The special nut (Figure 2) is fabricated by integrating a round table block, a ring block, and a square block.

**3.2. Theoretical Analysis of Mechanical Properties of Energy-Absorbing Devices.** During impact, existing energy-absorbing devices have large load fluctuations, which do not satisfy the mechanical performance requirements for anti-scour bolt; hence, it is necessary to design a new device [18–20]. The constant resistance energy-absorbing device is designed as a thin-walled circular tube that slides along the round table block of the special nut to achieve a constant resistance yield. Let the outer diameter, inner diameter, and wall thickness of the thin-walled circular tube be  $2R_0$ ,  $2r_0$ , and  $t$ , respectively (note that the inner diameter ( $2r_0$ ) is larger and smaller than the diameters of the left and right circles of the special-shaped nut round block, respectively). Through expansion, these outer and inner diameters are made to transition to the larger outer and inner diameters, denoted as  $2R_1$  and  $2r_1$ , of the rear thin-walled tube, respectively. The round nut angle of the special-shaped nut is  $\alpha$ , the axial compressive stress is  $\sigma_z$ , the radial compressive stress is  $\sigma_n$ , the hoop tensile stress is  $\sigma_\theta$ , and the friction coefficient between the inner wall of the thin-walled tube and special-shaped nut is  $\mu$ . To analyze the expansion force on the thin-walled circular tube, a circular ring-shaped element is obtained from the expansion area bounded by two planes normal to the axis of the tube, as shown in Figure 3 [21].

$$\begin{aligned} & (\sigma_z + d\sigma_z)\pi[(R+dR)^2 - (r+dR)^2] - \sigma_z\pi(R^2 - r^2) \\ & + 2\sigma_n\pi r dR + 2\frac{\mu\sigma_n\pi r}{\tan\alpha}dR = 0. \end{aligned} \quad (12)$$

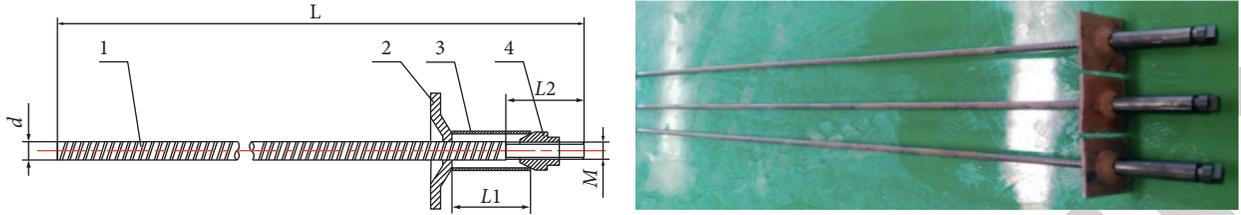


FIGURE 1: Energy-absorbing anti-impact anchor.

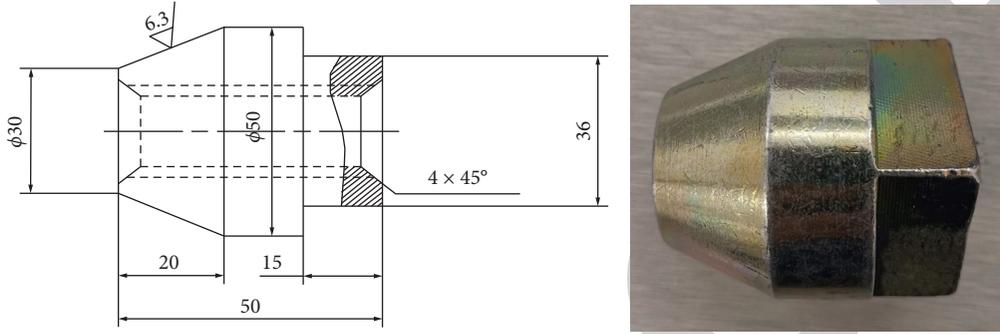


FIGURE 2: Diagram of special-shaped nut.

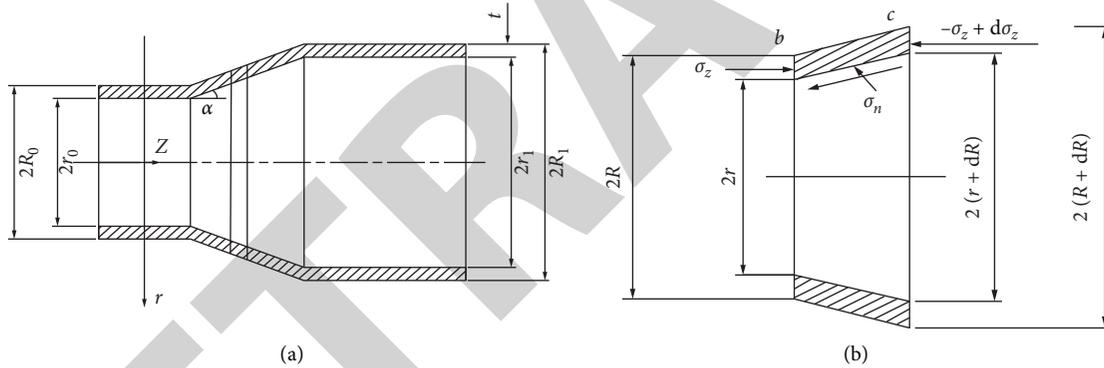


FIGURE 3: Diameter and base body. (a) Radius expansion diagram. (b) Primitive body force diagram.

Set the basic element in the Z-axis direction of the equilibrium equation.

Omitting the high-order trace yields the following:

$$(R^2 - r^2)d\sigma_z + 2[(R - r)\sigma_z + \sigma_n r (1 + \mu \cot \alpha)]dR = 0. \quad (13)$$

Assuming that  $\sigma_r$  is the combined stress of the radial compressive and frictional stresses of the toroidal base body, the following relationship can be introduced:

$$\sigma_n = \frac{\sigma_r}{1 - \mu \tan \alpha}. \quad (14)$$

If it is assumed that the wall thickness of the thin-walled tube remains constant during radius expansion, then the corresponding yield condition is

$$\sigma_z + \sigma_\theta = K, \quad (15)$$

where  $K$  is the plane deformation resistance, given as  $K = 1.155\sigma_s$ , and  $\sigma_s$  is the yield stress of the material.

For the stress analysis, half of the circular ring element is considered as shown in Figure 4.

The vertical balance equation is as follows:

$$2\sigma_\theta t = \int_0^\pi \sigma_r r d\theta \cdot \sin \theta. \quad (16)$$

Equation (15) is rewritten as equation (16).

$$\sigma_r = \frac{R - r}{r} (1.15\sigma_s - \sigma_z). \quad (17)$$

Combining equations (17) and (14) and substituting the results into equation (12) yield

$$\frac{d\sigma_z}{\sigma_z a - 1.15\sigma_s(a + 1)} = \frac{2dR}{R + r}, \quad (18)$$

where  $a = (1 + \mu \cot \alpha / 1 - \mu \tan \alpha) - 1$ .

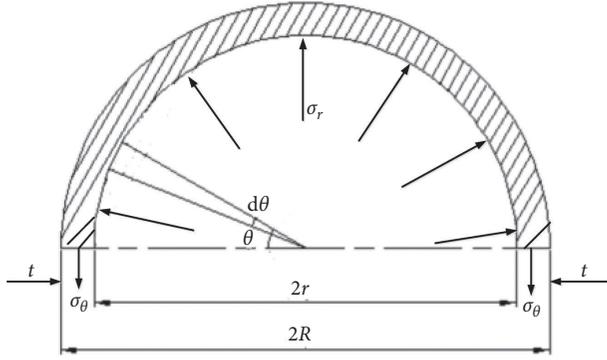


FIGURE 4: Half ring body force diagram.

When the integral of equation (18) is substituted into the boundary condition ( $R = R_0$ ,  $r = r_0$ , and  $\sigma_z = 0$ ), the yield stress of the constant energy-resistive device is given by the following:

$$\sigma_z = \beta \sigma_s \frac{a+1}{a} \left[ 1 - \left( \frac{R_1 + r_1}{R_0 + r_0} \right)^{2a} \right]. \quad (19)$$

In the foregoing,  $\beta = (K/\sigma_s)$ .

The yield force of the constant resistance energy-absorbing device can be obtained from equation (19), as follows:

$$F = \pi(R_0^2 - r_0^2)\sigma_z. \quad (20)$$

That is,

$$F_{\max} = 1.15\pi(R_0^2 - r_0^2)\sigma_s \frac{a+1}{a} \left[ 1 - \left( \frac{R_1 + r_1}{R_0 + r_0} \right)^{2a} \right]. \quad (21)$$

Based on equation (20), it can be concluded that the bearing capacity of the constant resistance energy-absorbing device is influenced by inner diameter, wall thickness, material yield strength, friction coefficient, and other parameters.

The energy absorbed can be calculated as

$$E = F\delta = 1.15\pi(R_0^2 - r_0^2)\sigma_s \frac{a+1}{a} \left[ 1 - \left( \frac{R_1 + r_1}{R_0 + r_0} \right)^{2a} \right] \left( L - \frac{r_1 - r_0}{\sin \theta} \right), \quad (22)$$

where  $L$  and  $\delta$  are the length and compression distance of the thin-walled tube, respectively.

**3.3. Numerical Simulation of Mechanical Properties of Constant Resistance Energy-Absorbing Device.** The model is established using ABAQUS finite element analysis software [22–28]. The special-shaped nut is assumed to be a 160 mm high rigid body with a 110 mm lower end diameter, a 100 mm upper end diameter, and a 10 mm high round table block. Considering the influence of the mechanical properties of thin-walled circular tube materials on energy absorption, three materials, specifically, T700L, Q550, and Q235, are simulated. The material parameters are shown in Tables 1 and 2. The thin-walled circular tube is 3 mm thick

and 150 mm long with a 105 mm inner diameter. The circular tube network is mainly a quadrilateral element with a 2 mm characteristic length. With all degrees of freedom of the special-shaped nut constrained, the thin-walled tube is placed above the nut, and a rigid plate is pressed axially from above the thin-walled tube at a constant speed of 1 m/s. An automatic point-to-surface contact mechanism is used between the rigid plate and circular tube. During the deformation process, the internal and external surfaces of the component are set to self-contact with a 0.3 friction coefficient.

The compression deformation process of the constant resistance energy-absorbing device is shown in Figure 5, and the force and energy absorption displacement curves are shown in Figures 6 and 7, respectively.

- (1) The various materials of the constant resistance energy absorbing-device have stable and repeatable deformation and failure modes during compression.
- (2) The constant resistance energy-absorbing device composed of different materials has a constant force during the yielding process, and the absorbed energy increases approximately linearly with the increase in compression distance. The yielding force and energy absorption results of the device during compression deformation are summarized in Table 1. (a) The yielding force and absorbed energy of T700L are 344 kN and 46.90 kJ, respectively, and the theoretical yielding force and absorbed energy are 347 kN and 45.47 kJ, respectively; the relative errors are 1% and 3%, respectively. (b) The simulated yielding force and absorbed energy of Q550 are 276 kN and 35.33 kJ, respectively, and the theoretical yielding force and absorbed energy are 262 kN and 35.87 kJ, respectively; the relative errors are 5% and 1%, respectively. (c) The simulated yielding force and absorbed energy of Q235 are 156 kN and 20.33 kJ, respectively, and the theoretical yielding force and absorbed energy are 112 kN and 15.10 kJ, respectively; the relative errors are 28% and 26%, respectively.

**3.4. Principles of Energy Absorption, Anti-Scour, and Anti-Scour Bolt Support.** For the energy-absorbing device to effectively function, its displacement force should be greater than the yielding force of the bar body; moreover, the breaking force of the bar body should be low. When the bearing capacity of the bolt is less than its yielding force, the energy-absorbing device will not yield to deformation. The principle of the support afforded by energy-absorbing anti-shock bolts is mainly reflected in two aspects: resistance and yield. The energy-absorbing device is not deformed and destroyed by the resisting bodies under the static pressure of the surrounding rock. The device is allowed to absorb energy to reduce impact when the ground exerts pressure. These processes are reflected in three aspects: first, the energy-absorbing device directly dissipates the impact energy of the surrounding rock

TABLE 1: Dimensions and anti-shock characteristics of thin-walled round pipes.

Component number	Material model	Wall thickness (mm)	Diameter (mm)	Length (mm)	Simulated $F_{max}$ (kN)	Theoretical $F_{max}$ (kN)	Relative error (%)	Theoretical $E$ (kJ)	Simulated $E$ (kJ)	Relative error (%)
1	T700L	3	105	150	344	347	1	45.47	46.90	3
2	Q550	3	105	150	276	262	5	35.87	35.33	1
3	Q235	3	105	150	156	112	28	20.33	15.10	26

TABLE 2: Material parameters.

Material model	$\text{kg}\cdot\text{m}^{-3}$	$E$ (GPa)	$\nu$	$\sigma_s$ (MPa)	$\sigma_b$ (MPa)	$\delta$ (%)
T700L	7850	210	0.3	720	790	16
Q550	7850	200	0.3	550	620	16
Q235	7850	200	0.3	235	380	16

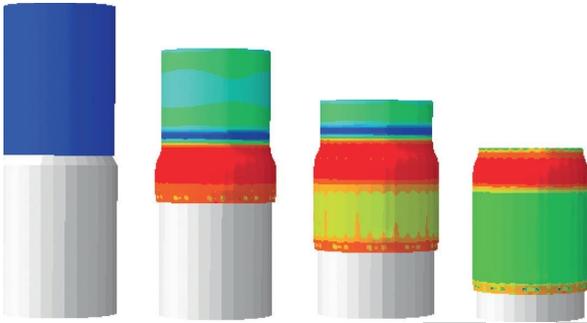


FIGURE 5: Deformation process of constant resistance energy-absorbing device.

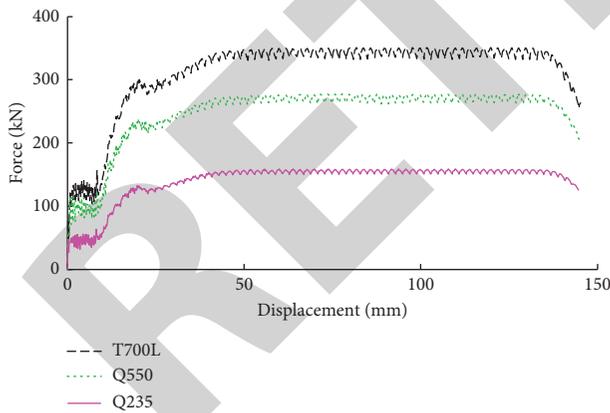


FIGURE 6: Material force-displacement.

through plastic deformation; second, the resulting conditions effectively improve the impact resistance of the anchor; third, the deformation space of the device provides a certain amount of energy release space for coal rocks. As a result, the surrounding rock impact energy is indirectly dissipated, the release and conversion of impact energy are effectively guided and controlled, and the impact energy is diminished in the buffering process of anchor bolts, thus

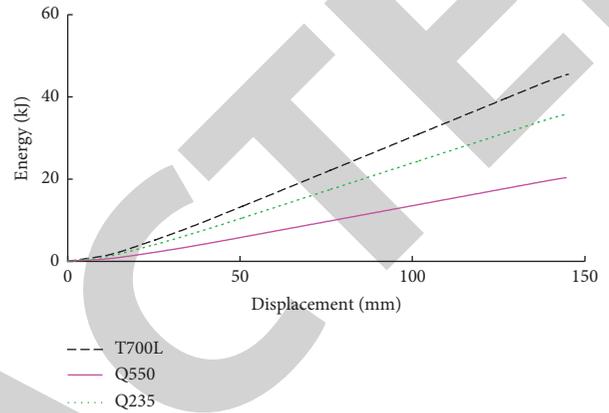


FIGURE 7: Energy absorption characteristics of materials.

ensuring the stability of the surrounding rock and support system of the roadway [29–31].

#### 4. Yielding Test Analysis of Energy-Absorbing Anti-Shock Anchor

The energy-absorbing device theoretically analyzed is made of Q235 material with an inner diameter, wall thickness, and length of 44, 3.5, and 150 mm, respectively. The size of the special-shaped nut is shown in Figure 2. The rod body is made of a 22 mm diameter rebar. Ordinary and energy-absorbing anchor bolts are subjected to static load and impact tests. These tests are performed on a 600 kN anchor bolt static load test bench (Figure 8) and a 300 kN anchor bolt impact test bench (Figure 9). The comparison of the energy-absorbing anchor before and after deformation is shown in Figure 10. The force-displacement curves of the common and energy-absorbing bolts tested are shown in Figure 11; Figure 12 depicts the energy absorption characteristic curves.

The tensile strength, yield distance, and absorbed energies of ordinary and energy-absorbing bolt are summarized in Tables 3 and 4.

- (1) Under static load, the tensile strength, yield distance, and absorption energy of ordinary anchor bolts are 505.46 MPa, 197 mm, and 31.99 kJ respectively, and those of the energy-absorbing anti-scour anchor bolts are 506.46 MPa, 329 mm, and 51.62 kJ, respectively. The tensile strength, yield distance, and absorption energy of the latter are 1, 1.67, and 1.61 times those of the former.



FIGURE 8: 600 kN test bench.



FIGURE 9: 300 kN test bench.

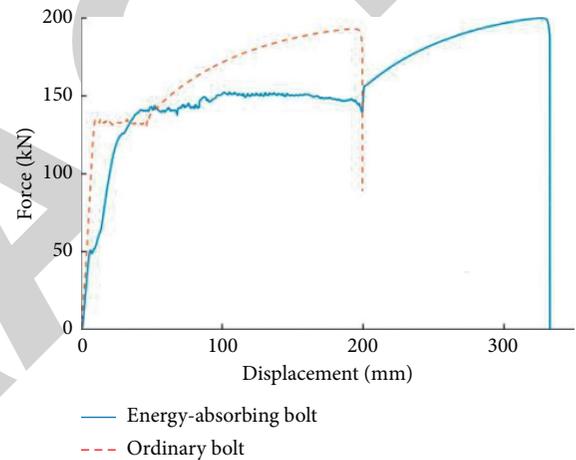


FIGURE 11: Force-displacement curves.



FIGURE 10: Before and after experiment contrast.

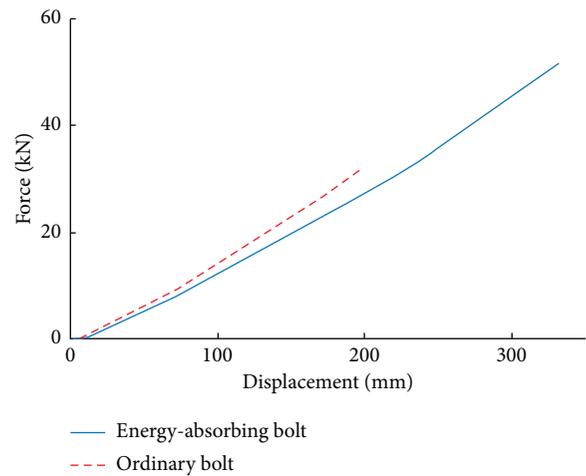


FIGURE 12: Energy absorption characteristics.

(2) Under impact load, the tensile strength, yield distance, absorbed energy, and impact time of ordinary bolt are 535.31 MPa, 195 mm, 35.08 kJ, and 0.15 s, and those of the energy-absorbing anti-shock bolt

are 534.84 MPa, 332 mm, 57.63 kJ, and 0.22 s, respectively. The tensile strength, yield distance, absorbed energy, and impact time of the latter are 1, 1.70, 1.64, and 1.47 times those of the former.

TABLE 3: Static loading of ordinary and energy-absorbing anti-shock bolt.

Bolt form	Tensile strength (MPa)	Abdicated distance (mm)	Absorbed energy (kJ)
335/22 ordinary bolt	505.46	197	31.99
MSGHS-335/22(1800)	506.55	329	51.62

TABLE 4: Impact loading of ordinary and energy-absorbing anti-shock bolt.

Bolt form	Tensile strength (MPa)	Abdicated distance (mm)	Absorbed energy (kJ)	Impact time (s)
335/22 ordinary bolt	535.31	195	35.08	0.15
MSGHS-335/22 (1800)	534.84	332	57.63	0.22

- (3) Under the action of impact load, the tensile strength of both ordinary and energy-absorbing anti-impact bolts increase by 5%. The absorbed energy also increases, but the effect of loading mode on bolt displacement is reduced. This demonstrates that the latter has a stronger capacity to absorb energy and longer impact resistance time than the former.

## 5. Conclusion

The energy balance equation of the energy-absorbing support and roadway surrounding rock system is established based on the principle of energy conservation. Moreover, the energy criterion for the instability of roadway supported by an energy-absorbing system is deduced. It can be concluded that this type of support can significantly enhance the anti-scour performance of the support system and effectively prevent the occurrence of rockburst. Accordingly, the foregoing provides a theoretical basis for energy-absorbing support and anti-scour design.

In view of the advantages afforded by energy-absorbing supports, a type of energy-absorbing anti-scour bolt, composed of rod body, tray, constant resistance energy-absorbing device, and special nut, is designed and developed. Based on the theoretical and numerical analyses of mechanical properties, it is concluded that the energy-absorbing device has a repeatable deformation failure mode and a constant yielding force. The test results indicate that the energy-absorbing anti-scour bolt has a stronger impact mechanical properties than the ordinary bolt.

This paper presents the principle involved in energy absorption and anti-scour. The energy-absorbing support effectively guides and controls the release and transformation of impact energy. It also consumes the impact energy in the process of bolt displacement and buffer to ensure the stability of the surrounding rock and support system.

## Data Availability

All data, models, and codes that support the findings of this study are available from the corresponding author upon reasonable request.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

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