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Full Length Article

Development of the rolling extrusion rock bolt with constant resistance and large deformation

Yundong Shou [a], Limin Guo [b], Xiaoping Zhou [a,*]

[a] School of Civil Engineering, Wuhan University, Wuhan 430072, China
[b] China Railway First Survey and Design Institute Group Co., Ltd, Xi'an 710043, China

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ABSTRACT

With the increasing excavation depth of underground engineering, engineering problems such as large deformation and rock burst caused by high geo-stress brings new challenges to the excavation and reinforcement of surrounding rock in deep underground engineering. The traditional rock bolt is prone to brittle fracture under high geo-stress due to its low elongation. Therefore, this work aims to develop a novel energy-absorbing bolt with constant resistance and large displacement to reinforce the surrounding rock with a risk of large deformation or rockburst. The novel energy-absorbing bolt refereed as rolling extrusion rock bolt (RE bolt) is mainly consists of sleeve tube with a variable cross-section, energy absorption slider with steel balls embedded, steel bar connected with the energy absorption slider. The rolling extrusion is adopted to produce the resistance force of the RE bolt, which avoids the sudden attenuation of resistance force and the abrasion of the energy absorption slider. The static pull test is conducted to study the resistance force and deformation characteristics of the RE bolt with different specifications. Results imply that the RE bolt has higher resistance force, larger deformation capacity and energy absorption capacity. The work of this study provides an effective solution for the reinforcement of surrounding rock in deep rock engineering.

1. Introduction

As an efficient supporting device, rock bolt has been widely used in transportation, water conservancy and hydropower, national defense, energy and other underground engineering fields, which can maximize the bearing capacity of surrounding rock and improve the stability of surrounding rock [1–6]. The main function of the rock bolt is to transfer the tension to the surrounding rock, so that the bearing capacity of the rock mass can be used to enhance the stability of the surrounding rock. Compared with the traditional support method, rock bolt has the advantages of simple installation, short construction period and lower cost. However, as the excavation depth of underground engineering increases, the high geo-stress in deep underground engineering causes a series of engineering problems, such as rock burst, large deformation under pressure, collapse etc., which present significant challenges to the excavation and reinforcement of surrounding rock of deep underground engineering [7–9]. Meanwhile, due to the low elongation and poor load-bearing capacity of traditional rock bolt, it is prone to brittle fracture under high geo-stress [10].

Therefore, for the deep rock engineering with risks of large deformation and rock burst, the rock bolt needs to have high strength to reinforce the rock mass and also have a large deformation capacity to adapt to the large deformation of the rock mass, i.e. energy-absorbing bolt. According the working principle, energy-absorbing bolt can be classified into two types: material-deformed energy-absorbing bolt and structure-deformed energy-absorbing bolt [10,11]. The material-deformed energy-absorbing bolt achieves the purpose of coordinating with the large deformation of the rock mass and providing reliable support by utilizing the yielding characteristics of the bolt material itself [12–15]. The D bolt developed by Li is a typical material-deformed energy-absorbing bolt [12]. D bolt is composed of a smooth steel and several anchors spaced along the bolt length. The smooth sections of the bolt between the anchors will undergo yielding deformation when the surrounding rock has large deformation, and static pull tests show that the elongation of the bolt is 14–20 %. The Versa-Superbolt developed by Cai is another typically material-deformed energy-absorbing bolt [13]. Under static and dynamic loads, the Versa-Superbolt absorbs the dynamic energy of the

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* Corresponding author.
E-mail address: xiao_ping_zhou@126.com (X. Zhou).

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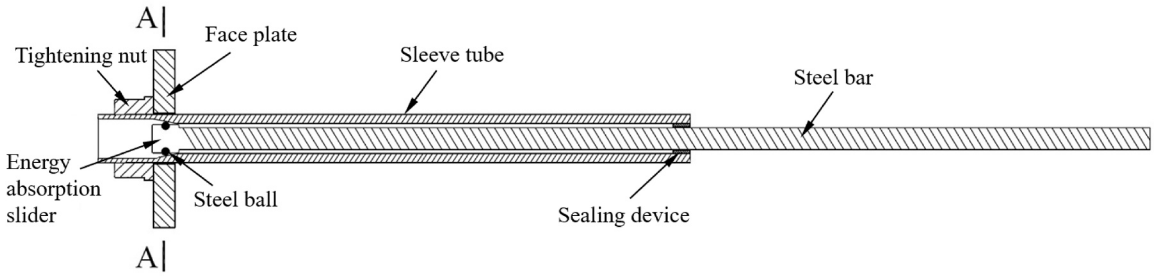
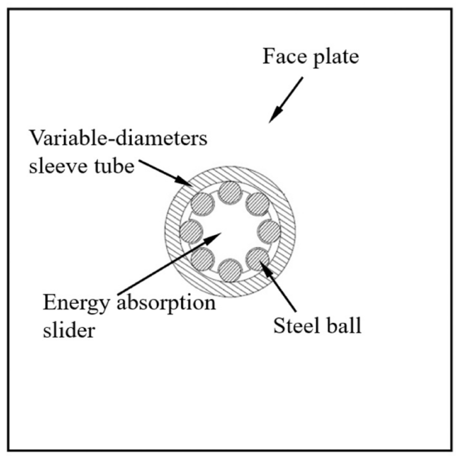


(a) Sectional view of the RE bolt



(b) Sectional view of A-A

Fig. 1. Structure diagram of the RE bolt.

surrounding rock through yield deformation and adapts to the large deformation of the surrounding rock. The test results show that the accumulated absorbed energy of the bolt is greater than 70 kJ. Wang et al. developed the lengthened bolt by utilizing the yielding deformation of materials and conducted a series of static and dynamic tests. [14]. The results showed that the elongation of the lengthened bolt was 17 % and the breaking load could reach 195 kN. However, the maximum deformation of material-deformed energy-absorbing bolt is generally lower than that of structure-deformed energy-absorbing bolt, mainly because the bolt material has a limited ultimate deformation value.

The structure-deformed energy-absorbing bolt achieves the purpose of coordinating with the large deformation of the rock mass and providing reliable support by utilizing the friction slip of mechanical members in the bolt, and its performance mainly depends on the parameters of energy-absorbing structure [16–25]. The structure-deformed energy-absorbing bolt include cone bolt [16], the Roofex rock bolt [17], the Garford bolt [18], the He-bolt [19–22], DC-bolt [23] and so on. The cone bolt consists of a smooth steel bar and a conical head mounted at the end of the bolt, which is designed to absorb the energy of rock deformation and provide the supporting force by utilizing the conical head to plough through the anchoring grout [16]. The Roofex rock bolt is a novel energy-absorbing rock bolt developed by Charette and Plouffe [17], and the bolt consists of smooth steel bar, energy absorption device and anchoring sleeve. When the tension applied to the Roofex rock bolt exceeds its critical value, the steel will undergo frictional sliding within the anchoring sleeve to adapt to the large deformation of the surrounding rock and release the deformation energy of the surrounding rock. The Garford rock bolt consists of mild steel solid bar, sliding anchor mechanism and coarse threaded steel sleeve crimped on to the end of the bolt [18]. The supporting force and deformation capability of the bolt are provided by the frictional sliding of the mild steel solid bar within the coarse threaded steel sleeve. Therefore, supporting force is determined by the diameter difference between the steel solid bar and sliding anchor mechanism, and the elongation of the bolt is mainly depended on the length of the coarse threaded steel sleeve. He-bolt is a typical energy-absorbing bolt developed by He et al., which is characterized by large elongation and constant resistance [19]. The bolt is composed of an elastically-deformable sleeve pipe and a cone-like piston that can slide inside it. A series of laboratory tests and numerical simulations were carried out to study the mechanical performance of He-bolt [20–22], and the results shown that the maximum displacement and the supporting force of the bolt were 1000 mm and 160 kN respectively. Yokota et al. invented a new energy-absorbing rock bolt, which is referred to as DC-bolt [23]. The bolt consists of the steel bar, the end anchor and the ring. The performance of the developed DC-bolt was studied by numerical simulations using laboratory tests, and the results indicated that DC-bolt possesses both the high supporting force and the deformable capacity.

As mentioned above, the existing material-deformed bolts and the structure-deformed bolts can provide supporting force and large deformation ability when the surrounding rock is subjected to deformation. However, due to the limited plastic yield deformation of the bolt material, the maximum deformation of the material-deformed bolt is generally low. The traditional structure-deformed bolt provides supporting force and large deformation ability by the relative sliding between the friction slider and the sleeve tube, which gives the structure-deformed bolt advantage in terms of large deformation. But when the friction between the friction slider and the sleeve tube changes from static friction to sliding friction, the supporting force of the bolt will suddenly change from a larger static friction force to a smaller sliding

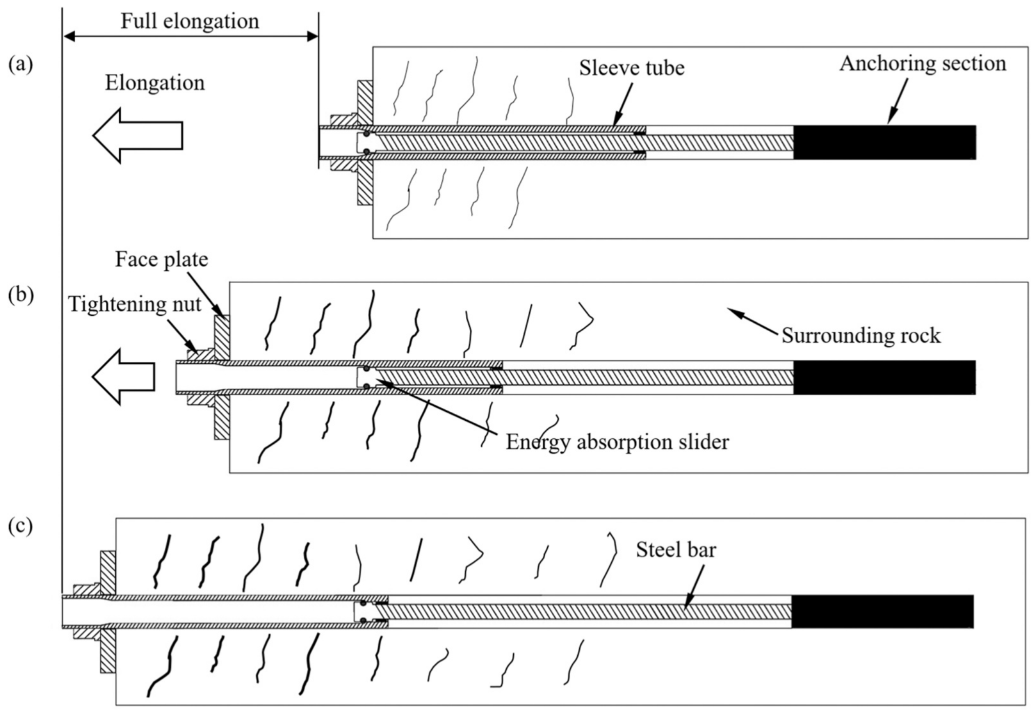


Fig. 2. Working principle of the RE bolt.

friction force, which causes the strain energy of the surrounding rock to be released instantly and results in a certain accident risk [10]. In addition, the friction slider will gradually wear out during the sliding process, which will gradually reduce the diameter of the friction slider and decrease the friction force between the friction slider and the sleeve tube, ultimately leading to a gradual decrease or even complete loss of the bolt supporting force.

Therefore, in order to overcome the shortcomings of the traditional energy-absorbing bolts, a novel energy-absorbing bolt with constant resistance and large displacement is developed in this paper. According to its working principle, the bolt is referred as rolling extrusion rock bolt (abbreviated as the RE bolt). The rolling extrusion between the energy-absorbing sleeve tube and high strength steel balls is employed to provide the supporting force for the RE bolt, which solves the problem of sudden change and decrease of supporting force of traditional structure-deformed energy absorbing bolt under tensile deformation. The bolt can continuously provide constant supporting force for the large deformation surrounding rock without breaking, which has important engineering application value.

2. Development of the RE bolt

2.1. Structure

The structure-deformed energy-absorbing bolt has a significant advantage in large deformation and energy absorption. Based on previous research on large deformation energy-absorbing device, the rolling extrusion rock bolt (RE bolt) with controllable and constant support resistance and large deformation ability is proposed in this study. The structure diagram of RE bolt is shown in Fig. 1. The RE bolt is composed of a steel bar, a sleeve tube, an energy absorption slider attached at the end of the steel bar, steel balls embed in the energy absorption slider, sealing device, a face plate and a tightening nut. The length of the steel bar can be adjusted according to the practical project needs. One end of the steel bar is the anchoring section, which is anchored in the rock mass. The other end the steel bar is connected with the energy absorption slider and placed in the sleeve tube. The energy absorbing slide is a steel cylinder with annular grooves in which several high-strength steel balls are embedded, and the number and diameter of steel balls depend on the design supporting resistance value of the RE bolt. The sleeve tube is a seamless steel pipe with variable inner diameter. In order to facilitate the energy absorption slider to enter the working section of the sleeve tube, a short section with a larger inner diameter is bored at the end of the sleeve tube, as shown in Fig. 1(a). A sealing device is installed at the other end of the sleeve tube to prevent groundwater from entering the sleeve tube and corroding the energy absorption mechanism. The length of the sleeve can be adjusted according to the allowable deformation of the surrounding rock, but it must be less than the allowable deformation. The tightening nut and face plate as the surface retention elements to provide the sleeve tube with forces in the opposite direction of the steel bar.

It should be noted that outer diameter of the energy absorption slider embedded with steel balls is larger than the inner diameter of the sleeve tube in the working section, so that the steel balls produce rolling extrusion motion in the inner wall of the sleeve tube, and then generating sufficient support resistance. Moreover, material of the energy absorbing slider must have sufficient shear strength to prevent it from being cut by the steel ball when the bolt is stretched.

2.2. Working principle

The working principle of the RE bolt is shown in Fig. 2. The anchoring section of the steel bar and stable surrounding rock are anchored by resin or cement grouting, and the unstable surrounding rock on the sidewall of the cave is reinforced by the stable surrounding rock through the anchoring section, steel bar, sleeve tube, face plate and tightening nut. Fig. 2(a) shows the initial working state of the RE bolt where the energy absorption slider located at the variable diameter position of the sleeve tube. When large deformation of surrounding rock or rock burst occurs in the tunnel, elongation nut, face plate and sleeve tube will move along with the deformation of the free surface of surrounding rock, while the steel bar is anchored in the stable rock mass and does not move. Therefore, the sleeve tube and the steel bar will move relative to each other, and the energy absorbing slider embed with

Fig. 3. RE bolt specimen for pull tests.

steel balls at the end of the steel bar will have rolling extrusion movement in the inner wall of the sleeve tube since its outer diameter is larger than the inner diameter of the sleeve tube, as shown in Fig. 2(b). In this process, the RE bolt is stretched, and a lot of energy released by surrounding rock is dissipated to maintain the stability of surrounding rock.

The resistance force of the RE bolt caused by the rolling extrusion between the steel balls embedded in the outer side of energy absorption slider and the inner wall of the sleeve tube mainly depends on the difference between the outer diameter of the energy absorbing slider containing the steel ball and the inner diameter of the sleeve, and the number of steel balls will also affect the magnitude of resistance force. The rolling extrusion is adopted to produce the resistance force of the RE bolt, which avoids the problem of sudden drop of resistance force from static friction force to dynamic friction force when the traditional energy-absorbing bolt is deformed, and improves the support ability of bolt. Moreover, the rolling extrusion of high-strength steel balls in the sleeve will not wear the ball, which overcomes the problem of reducing the resistance force caused by the wear of friction block in the deformation process of traditional energy-absorbing bolts. Meanwhile, due to the adoption of this unique energy-absorbing structure, the RE bolt a very large elongation. Fig. 2(c) shows the working state of the RE bolt supporting the deformation of the rock mass when it is fully elongation.

3. Bolt pulling tests

3.1. Specimens preparation

The resistance force and deformation ability are two important indexes measure the performance of the energy-absorbing bolt. In this section, static pull tests are conducted to investigate the resistance force and deformation characteristics of the RE bolt with different specifications. According to the structure and the working principle of the RE bolt introduced in Section 2, the new bolt specimens for pull tests are fabricated, as shown in Fig. 3. The sleeve tube is constructed from 20# low carbon steel, a material that demonstrates high strength and ductility. The elastic modulus of the 20# steel is 206 GPa, the Poisson's ratio is 0.3, and the yield strength is 245 MPa. The material of the steel bar and energy absorption slider are 45# medium carbon steel, which has good performance in shear strength. The elastic modulus and Poisson's ratio of the steel are the same as that of 20# steel, and the shear strength of the steel is 178 MPa. Steel balls with a high load-bearing capacity and a hardness rating of HRC 60 are chosen.

In order to investigate the influence of the outer diameter of the energy absorption slider, the diameter of steel bass, the number of steel balls and the thickness of sleeve tube on the resistance force and deformation ability of the RE bolt, four specifications bolts with different numbers are fabricated. The Geometric parameters of the four types bolts are indicated in Fig. 4. In these specimens, the outer diameter sleeve tube, the length of sleeve tube and steel bar are constant, which are 50 mm, 650 mm and 1500 mm respectively. The detailed geometric parameters of the specimens are shown in Table 1.

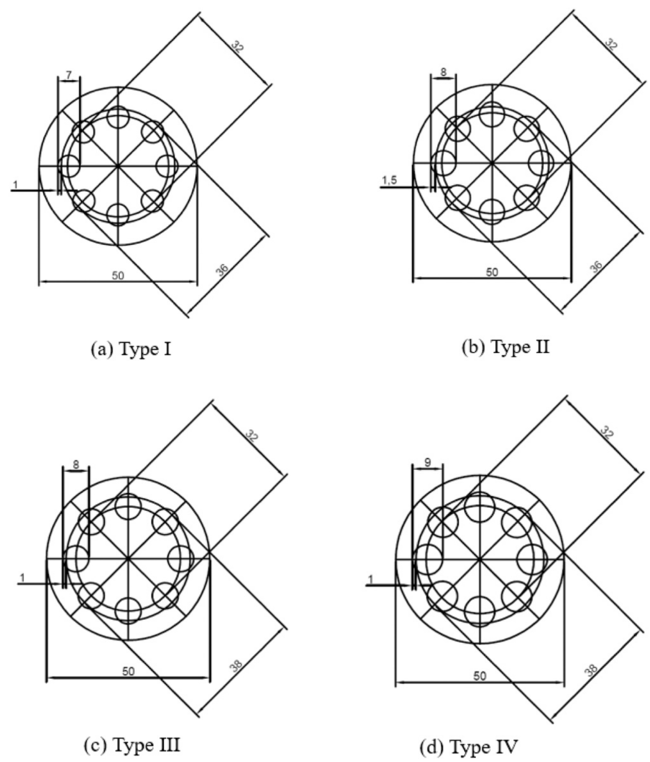


Fig. 4. Geometric parameters of four specifications bolts.

3.2. Test facilities and process

Due to the large deformation of the RE bolt proposed in this paper,

Table 1
Detailed geometric parameters of the bolt.

Specimen No.	Geometric parameters of energy absorption slider			Geometric parameters of sleeve tube	
	Outer diameter of energy absorption slider (mm)	Diameter of steel balls (mm)	Number of steel balls	Inner diameter of sleeve tube (mm)	Thickness of sleeve tube (mm)
I-1	38	7	11	36	7
I-2	38	7	12	36	7
I-3	38	7	13	36	7
II-1	39	8	7	36	7
II-2	39	8	8	36	7
II-3	39	8	9	36	7
III-1	40	8	8	38	6
III-2	40	8	9	38	6
III-3	40	8	10	38	6
IV-1	40	9	8	38	6
IV-2	40	9	9	38	6
IV-3	40	9	10	38	6

traditional tensile testing machines, which have a small stroke and an inability to install longer test specimens, cannot meet the requirements of this experiment. A temporary large deformation tensile testing system is assembled, as shown in Fig. 5. This testing system is composed of reaction frame, displacement sensor, tension loading sensor, loading system and data collection system. The maximum tensile load of the loading system is 750 kN, the maximum tensile space is 800 mm, and the range of the tensile speed 10–100 mm/min. The data collection system is capable of real-time recording and displaying of load variations with displacement. The length range of allowable bolt specimen of the testing system is 500–3000 mm.

The procedure of the pulling test is as follows: (1) The end of the RE bolt is fixed on the base of the reaction frame through the face plate, and the other end of the bolt is fixed on the tension loading sensor by the reinforcement anchor and the customized component; (2) The tension sensor is connected to a jack, through which a tension loading with a speed of 60 mm/min is applied to drive the steel bar to slide until the energy absorbing slider slides out of the sleeve tube, the stretching process of the RE bolt is shown in Fig. 6; (3) Real-time data collection is carried out through the data collection system connected to displacement sensor and tension sensor.

3.3. Experimental results

3.3.1. Load displacement curves

Fig. 7 shows the load displacement curves of type I RE bolt with

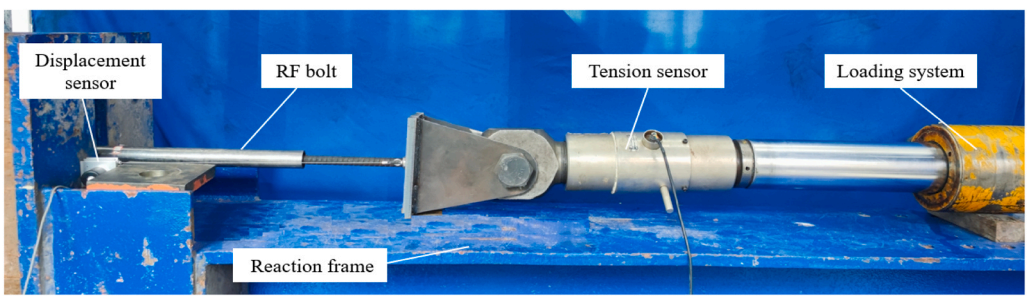


Fig. 5. The large deformation tensile testing system.

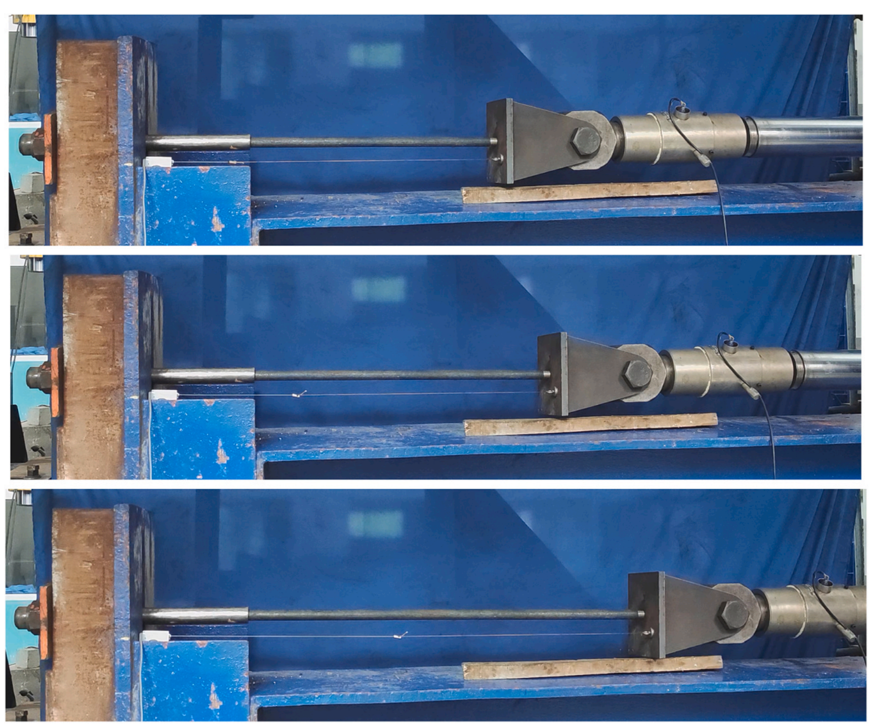


Fig. 6. The stretching process of the RE bolt.

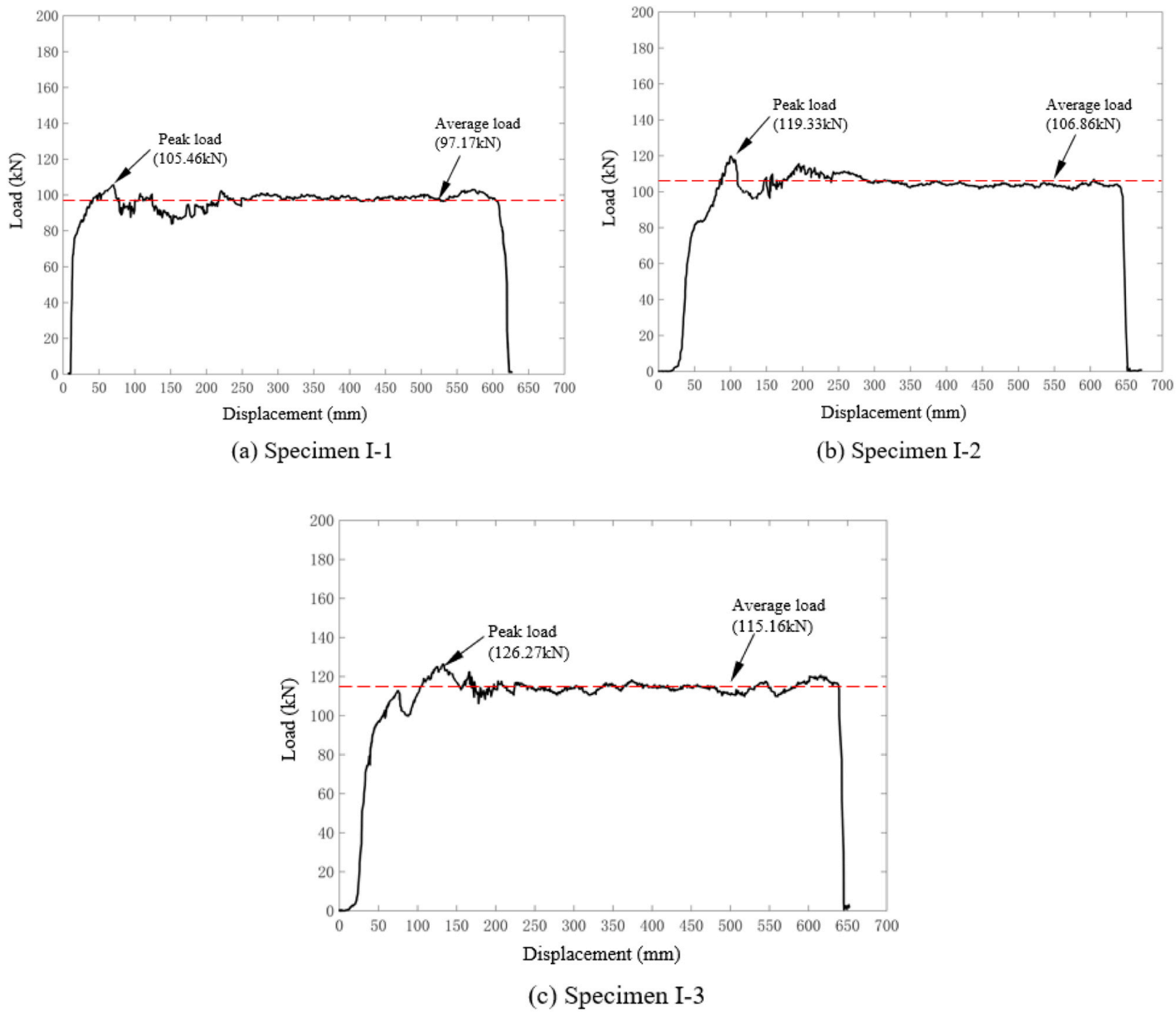


Fig. 7. The load displacement curves of type I RE bolt.

different numbers of steel balls through the static pulling test. It can be observed from the figure that the resistance force of the three specimens rapidly reaches to the peak value at a small displacement within about 100 mm, which indicates the new rock bolt can produce sufficient resistance force under minimal elongation just like traditional rock bolt. After reaching the peak value, the resistance force experiences a slight decrease. This occurs as the steel balls embedded in the energy absorbing slider rolling against the inner wall of the sleeve tube which causes the part of the inner wall of the sleeve tube contacted with the steel balls to yield, thereby reducing the strength of the low-carbon steel from the upper yield point to the yield value [24]. Then, with the increase of displacement, the resistance force tends to remain constant until the bolt fails.

Specimen I-1 contains 11 steel balls in the energy absorbing slider. As shown in Fig. 7(a), the peak resistance force of the specimen is 105.46 kN and the average resistance force of the specimen is 97.17 kN. The specimen I-2 contains 12 steel balls in the energy absorbing slider which is one more steel ball than that of specimen I-1. The peak resistance force and the average resistance force of specimen I-2 are 119.33 kN and 106.86 kN respectively. The specimen I-3 contains 13 steel balls in the energy absorbing slider. The peak resistance force and the average resistance force of the specimen are 126.27 kN and 115.16 kN respectively.

Fig. 8 shows load displacement curves of type II RE bolt with different numbers of steel balls through the static pulling test. Similarly, with the increase of the displacement, the resistance force of the type II RE bolt increases rapidly to the peak value at a small displacement within about 100 mm, and then the resistance force drops slightly. Finally, the resistance force of the bolt remains constant under large deformation.

Compared with the type I RE bolt, the energy absorption slider of the type II RE bolt is embedded with larger diameter steel balls. However, due to the diameter limitations of the sleeve tube, fewer steel balls can be installed. Specimen II-1 contains 7 steel balls in the energy absorbing slider. As shown in Fig. 8(a), the peak resistance force of the specimen II-1 is 151.50 kN and the average resistance force of the specimen is 138.53 kN. The specimen II-2 contains 8 steel balls in the energy absorbing slider which is one more steel ball than that of specimen II-1. The peak resistance force and the average resistance force of specimen II-2 are 163.51 kN and 151.10 kN respectively. The specimen II-3 contains 9 steel balls in the energy absorbing slider. The peak resistance force and the average resistance force of the specimen are 181.75 kN and 162.26 kN respectively.

As shown in Fig. 9, the load displacement curves variation law of type III RE bolt is similar to that of type I and type II RE bolt. Compared with the type II RE bolt, type III RE bolt has a larger inner diameter and a

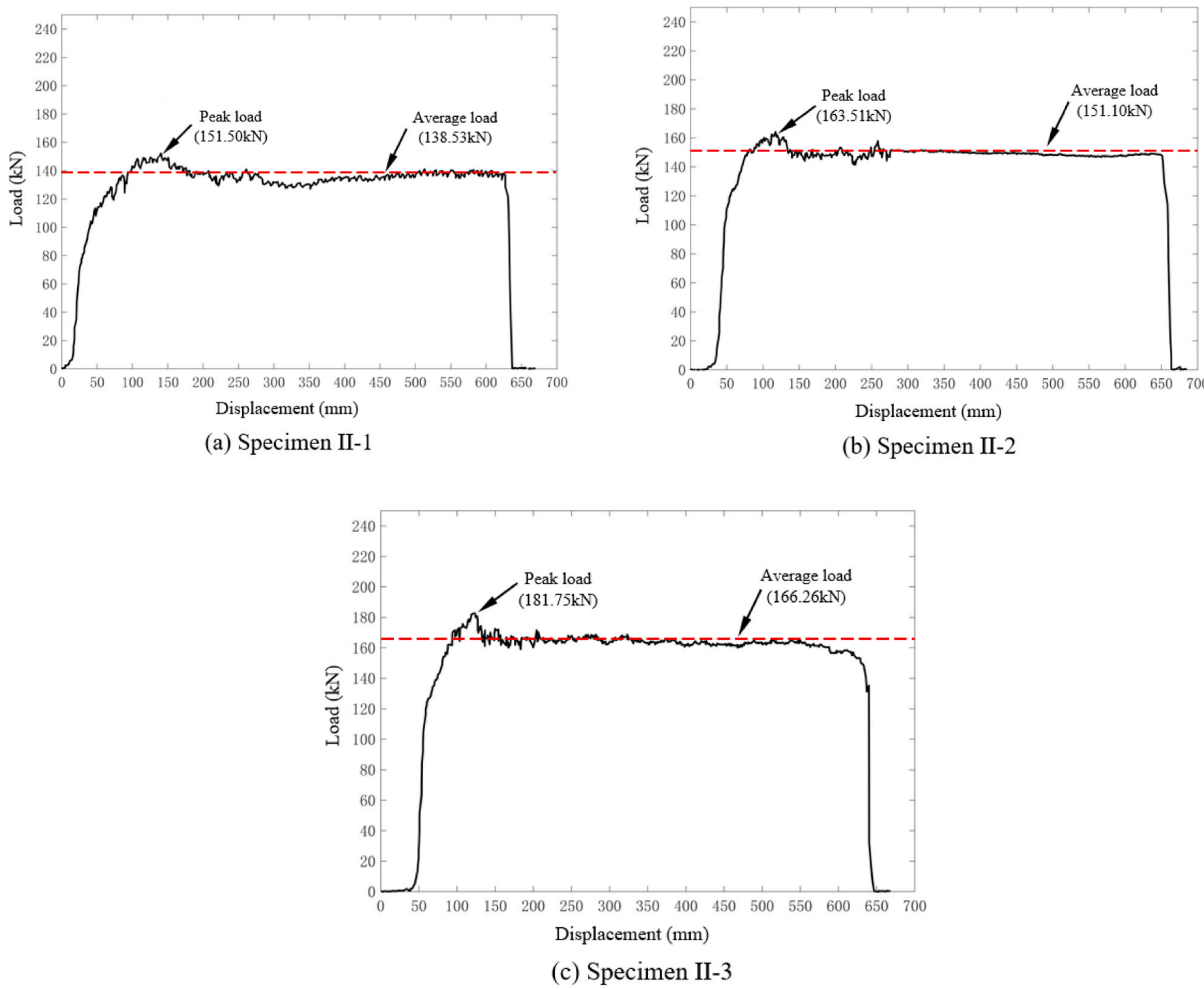


Fig. 8. The load displacement curves of type II RE bolt.

thinner shell wall of sleeve tube, which has significantly influenced the strength of the bolt. Therefore, the energy absorption slider can be embedded more steel balls. Specimen III-1 contains 8 steel balls in the energy absorbing slider. Fig. 9(a) illustrates that the peak resistance force for specimen III-1 reaches 121.26 kN, while the average resistance force for the specimen stands at 107.60 kN. The energy absorbing slider in specimen III-2 holds 9 steel balls, which is one more than the number of steel balls in specimen III-1. The peak resistance force and the average resistance force of specimen III-2 are 128.75 kN and 120.37 kN respectively as shown in Fig. 9(b). The specimen III-3 contains 10 steel balls in the energy absorbing slider, and the specimen has a peak resistance force of 147.43 kN and an average resistance force of 137.45 kN as shown in Fig. 9(c).

Fig. 10 shows the load displacement curves of type IV RE bolt with different numbers of steel balls. Apparently, there are similar tendency among the load displacement curves for specimen IV-1 to IV-3. It is found from the figure that the resistance force of the three specimens rapidly increases to the peak value at a small displacement within about 50 mm. After reaching the peak value, the resistance force experiences a slight decrease. Then, with the increase of displacement, the resistance force tends to remain constant until the bolt fails. Compared with the type III RE bolt, type IV RE bolt has a larger diameter of steel balls. Fig. 10(a) illustrates that the peak resistance force for specimen IV-1 reaches 127.63 kN, while the average resistance force for the specimen stands at 116.58 kN. The peak resistance force and the average resistance force of specimen IV-2 are 138.85 kN and 126.36 kN respectively as shown in Fig. 10(b). The specimen IV-3 has a peak resistance force of 151.63 kN and an average resistance force of 140.86 kN, as shown in Fig. 10(c).

3.3.2. Failure characteristics

In the tests, under the tensile action of the hydraulic jack, the energy absorbing slider is pulled into the sleeve tube, and the resistance force is generated by the rolling extrusion action between the embedded balls and the inner wall of the sleeve tube. As the jack continues to stretch, the energy-absorbing slider continues to slide and produce a constant resistance force until it slides out from the other end of the sleeve tube and loses the resistance force. Therefore, the failure mode of the new rock bolt is that the energy absorbing slider slides out of the sleeve tube. Fig. 11 shows the actual failure characteristics of the RE bolt after the test. As can be seen from the figure, under the rolling extrusion action of the steel balls, gouging scratches equal to the number of steel balls are generated on the inner wall of the sleeve tube, and with the slide of the energy absorption slider. As the energy absorption slider slides out of the sleeve tube, a small amount of iron filings produced by the steel balls rolling against the inner wall of the sleeve tube are brought out.

It should be noted that the wall thickness of the sleeve tube must be thick enough to prevent the sleeve tube from breaking due to insufficient radial strength during the operation of the RE bolt. Moreover, the material of the energy-absorbing slider must possess sufficient shear

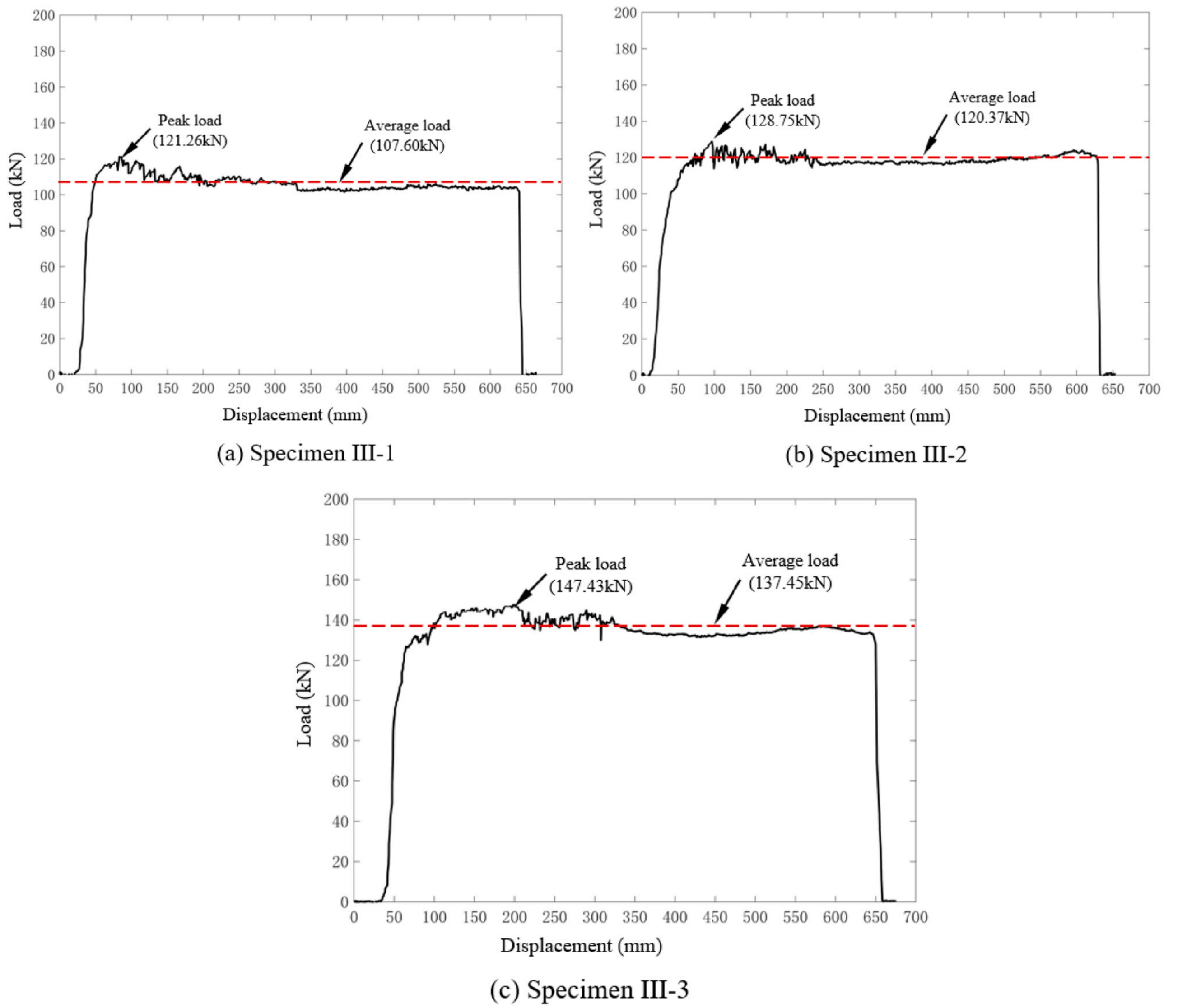


Fig. 9. The load displacement curves of type III RE bolt.

strength to prevent it from being shear by the reaction force of the steel balls.

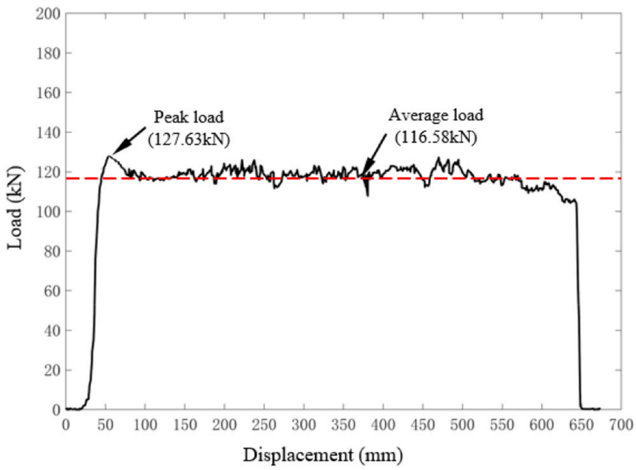
4. Discussion

4.1. Influences of the number of steel balls on resistance force

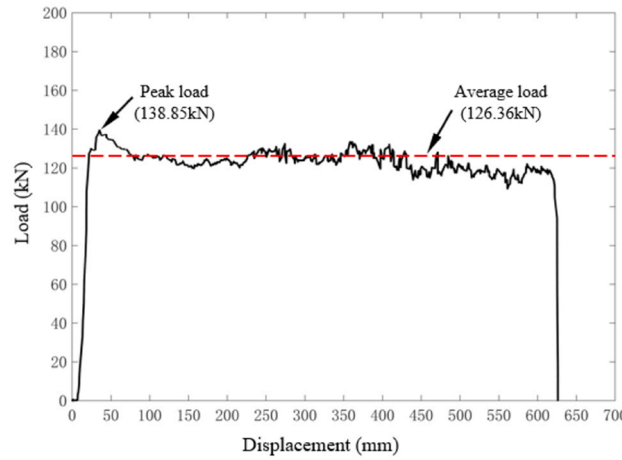
The resistance force of the RE bolt is produced by the rolling extrusion between the steel balls embedded in the outer side of energy absorption slider and the inner wall of sleeve tube. Apparently, the number of the steel balls significantly affect the magnitude of resistance force. The relationships between resistance force and number of steel balls for type I-IV RE bolt from the tests are shown in Fig. 12. Obviously, trend of resistance force with the number of steel balls for type I-IV RE bolt are nearly the same. The peak resistance force and average resistance force of the four types of RE bolts exhibits a linear increase in relation to the number of steel balls. Therefore, for the same type of RE bolt, the resistance force of the bolt can be conveniently changed by adjusting the number of steel balls, so as to be applied to different practical projects. Moreover, the peak resistance force is larger than the average resistance force. This is because the peak resistance force is caused by the upper yield point of the low carbon steel in the inner wall of the sleeve tube, while the average resistance force is produced by the yield strength of the low carbon steel in the inner wall of the sleeve tube. The upper yield point is greater than the yield strength as shown in Fig. 13.

4.2. Influences of the diameter of steel balls on resistance force

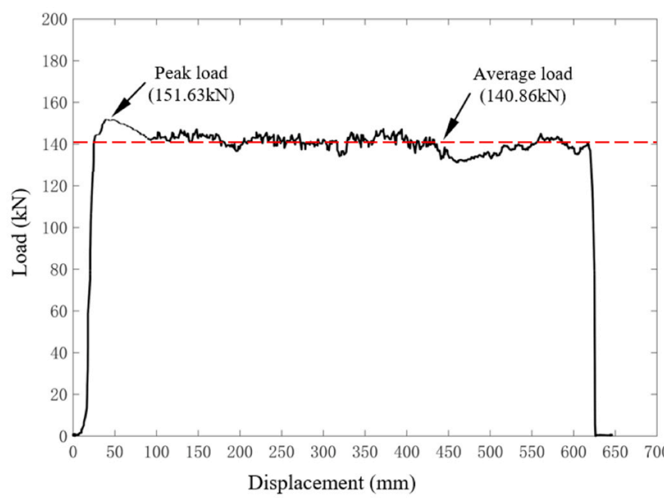
Fig. 14 shows the average resistance force of RE bolt for different diameter of steel ball embedded in the outer side of energy absorbing slider. The bolt with a steel ball diameter of 8 mm adopts the same geometric parameters of sleeve tube and energy absorbing sleeve outer diameter as the bolt with a steel ball diameter of 9 mm, the detail parameters are shown in Table 1 for specimen III-1, III-2, III-3 and specimen IV-1, IV-2, IV3. Obviously, it can be found from Fig. 14 that increasing the diameter of steel balls will slightly increase the resistance force of the RE bolt under the condition of the same number of steel balls. This is due to the steel balls with larger diameters have a larger contact area when rolling against the inner wall of sleeve tube, which results in a greater resistance force. Moreover, the increase of resistance force by increasing the diameter of steel balls is lower than that by increasing the number of steel balls. This indicates that the resistance force of RE bolt can be fine-tuned by selecting steel balls with different diameters to adapt to different practical projects.



(a) Specimen IV-1



(b) Specimen IV-2



(c) Specimen IV-3

Fig. 10. The load displacement curves of type IV RE bolt.

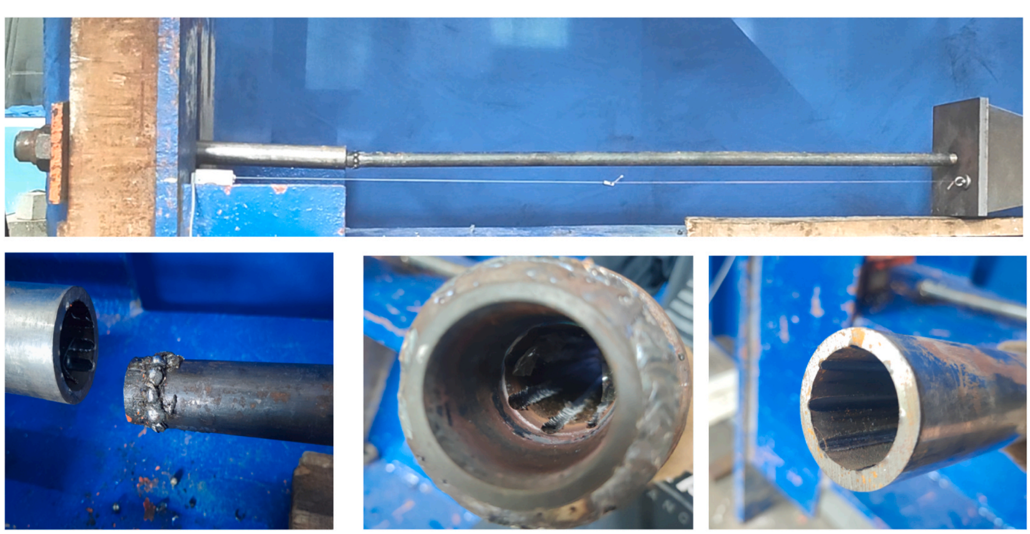


Fig. 11. Failure characteristics of the RE bolt.

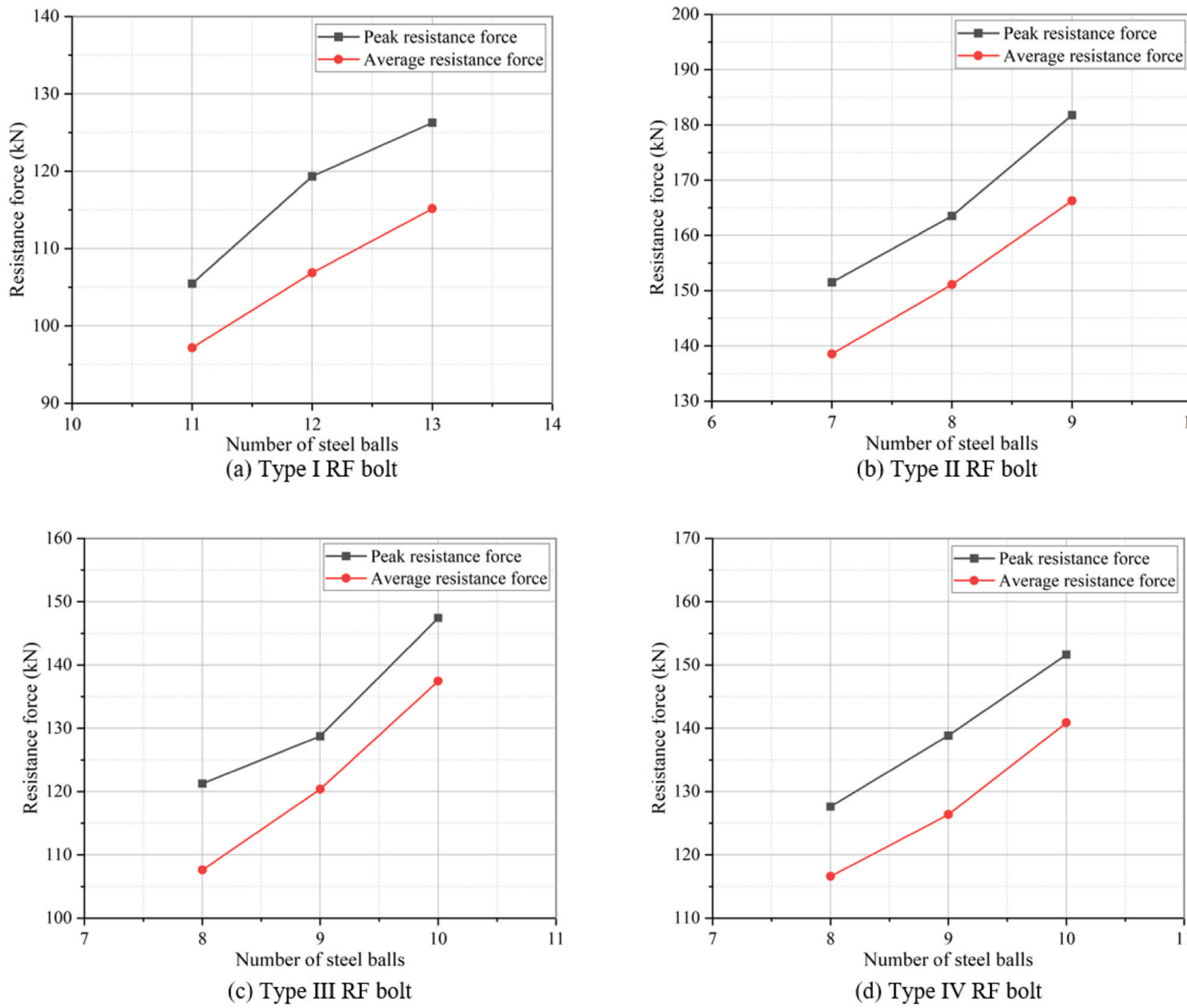


Fig. 12. The relationships between resistance force and number of steel balls for type I-IV RE bolt.

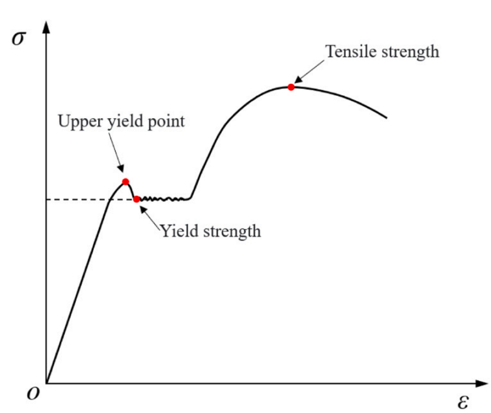


Fig. 13. The stress-strain curve of mild steel.

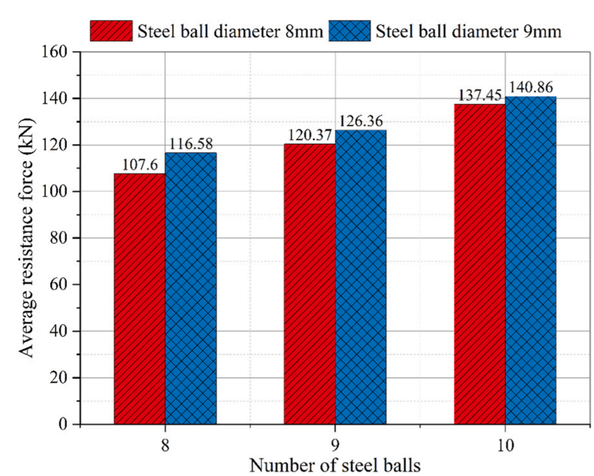


Fig. 14. The average resistance of RE bolt for different diameter steel ball.

4.3. Influences of the difference between the outer diameter of energy absorbing slider and the inner diameter of sleeve tube on resistance force

Fig. 15 shows the average resistance force of RE bolt for different ΔD, where ΔD represents the difference between the outer diameter of energy absorbing slider and the inner diameter of sleeve tube. The data in Fig. 15 are obtained from specimen II-2, II-3 III-1 and III-2, and the detail geometric parameters of these specimens are shown in Table 1. Apparently, with the increase of the difference between the outer diameter of energy absorbing slider and the inner diameter of sleeve tube, the

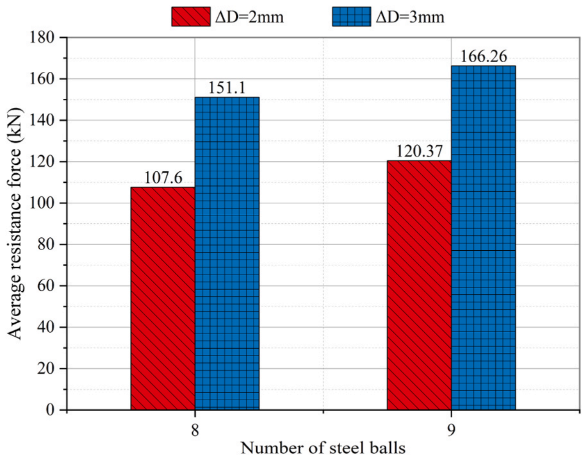


Fig. 15. The average resistance force of RE bolt for different ΔD.

Table 2
The amount of energy absorbed of the RE bolt.

Specimen No.	Average resistance force (kN)	Maximum deformation (mm)	Absorbed energy (kJ)	Energy absorption ability (kJ/m)
I-1	97.17	605.7	58.65	96.83
I-2	106.86	629.7	63.51	100.86
I-3	115.16	632.4	69.48	109.87
II-1	138.53	631.2	82.01	129.93
II-2	151.10	639.4	91.58	143.23
II-3	166.26	605.4	95.39	157.57
III-1	107.60	623.8	64.36	103.17
III-2	120.37	620.9	71.32	114.87
III-3	137.45	621.8	82.32	132.39
IV-1	116.58	630.8	71.79	113.81
IV-2	126.36	625.1	75.44	120.68
IV-3	140.86	618.8	85.43	138.06

average resistance force of RE bolt increases significantly. This is attributed to the fact that a larger outer diameter of the energy-absorbing slider substantially enhances the contact area and pressure between the steel balls and the inner wall of the sleeve tube, consequently escalating the resistance force of the bolt. It should be noted that the difference between the outer diameter of energy absorbing slider and the inner diameter of sleeve tube should not be too large to prevent the sleeve tube from breaking due to excessive pressure exerted by the steel balls on the inner wall of the sleeve tube.

4.4. Energy absorption ability

The RE bolt absorbs the energy generated by large deformation or rock burst of the surrounding rock through the rolling extrusion of the energy absorbing slider in the sleeve tube, and releases it in the form of heat. Therefore, the energy absorption ability is also an important index to measure the performance the RE bolt. According to the work-energy principle, the energy absorbed by the RE bolt is equal to the area enclosed by the load displacement curve and the X-axis, as show in Figs. 7–10. The absorbed energy of the specimens are calculated by the Origin software and the detailed results are listed in Table 2. It can be found from the table that a lager average resistance force allows the RE bolt to absorb more energy. The maximum energy absorption ability is 157.57 kJ/m, which is higher than the energy-absorbing bolt proposed by other researchers [19,25]. Moreover, the deformation of the bolt in this test is range from 605.7 mm to 639.4 mm, which is because the maximum deformation of the RE bolt is limited by the size of the sleeve tube, and the size of the sleeve tube used in the test is 650 mm. According to the working principle in Section 2.2, the energy absorbing slider will not be worn during rolling extrusion of the inner wall of sleeve tube so that the resistance remains constant. Therefore, the deformation of bolt can be improved by increasing the sleeve tube length.

5. Conclusion

In this study, a novel energy-absorbing bolt (referred as RE bolt) with constant resistance and large displacement ability is developed to reinforce the surrounding rock with a risk of large deformation or rockburst. The resistance force of the RE bolt is caused by the rolling extrusion between the steel balls embedded in the outer side of energy absorption slider and the inner wall of the sleeve tube. A series of static pull tests are carried out to investigate the resistance force and deformation characteristics of the RE bolt with different specifications. The main conclusions are drawn as follows:

(1) The rolling extrusion is employed to produce the resistance force of the RE bolt, which avoids the problem of sudden drop of resistance force from static friction force to dynamic friction force when the traditional energy-absorbing bolt is deformed, and the support ability of the bolt is improved.

(2) The high-strength steel balls will not be worn during rolling extrusion in the sleeve tube, so as to overcome the problem of reducing the resistance force caused by the wear of friction block in the deformation process of traditional energy-absorbing bolts.

(3) The RE bolt has high energy absorption ability ranging from 96.83 kJ/m to157.57 kJ/m. The maximum deformation of the RE bolt is limited by the sleeve size, so increasing the sleeve length can increase the maximum deformation and energy absorption capacity of the bolt.

(4) The factors affecting RE bolt resistance force are the difference between the outer diameter of energy absorbing slide and the inner diameter of sleeve, the number of steel balls and the diameter of steel balls. It means the resistance force can be conveniently changed by adjusting these factors, so as to be applied to different practical projects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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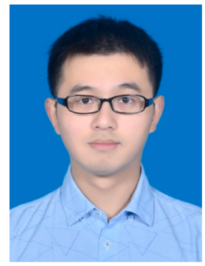

Dr. Yundong Shou received his PhD in civil Engineering from Chongqing University, China in 2017 and then took the position of lecturer and associate research fellow at Wuhan University. He has conducted extensive research work pertaining to the multi-physical field coupling of fractured rock, the mechanics of deep rock mass, and peridynamics, resulting in a notable series of significant research outcomes. His research findings have been recognized with three provincial and ministerial science and technology awards. In addition, he also presided over a number of national scientific research projects.

Prof. Xiao-Ping Zhou received his PhD degree at Chongqing University, China in 2000. Following the completion of his doctoral studies, he embarked on a Postdoctoral Fellowship at Shanghai Jiao Tong University and then took the position of lecturer, associate professor and professor after returning Chongqing University. Prof. Xiao-Ping Zhou has long been committed to the scientific research work of slope landslide prevention and control technology in mountainous areas/reservoir areas, deep rock mass mechanics and its disaster-causing mechanism and early warning, and has achieved a series of important research results. His scientific research achievements have won two first prizes of scientific and technological progress at provincial and ministerial level, one first prize of natural Science and Technological Invention of China Society of Rock Mechanics and Engineering, and one first prize of natural science of the Ministry of Education. He has authorized 35 national invention patents, published 1 monograph, published more than 300 SCI papers (including 12 ESI highly cited papers, 1 ESI hot paper), and more than 200 EI papers. The cumulative number of citations is more than 7000 times, and the H-index is 48. He has presided over more than 10 key projects of Natural Science Foundation, major scientific research instrument development projects and 973 projects.