Experimental Investigation on Mechanical Behavior of Anchor and Shotcrete Support System Under Axial Pull-out Action

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Abstract

Based on axial pull-out performance tests of anchor and shotcrete support system with three types of plates and two kinds of shotcretes (plain and steel fiber reinforced concrete) conducted by use of the multi-functional testing system. The mechanical behavior of the anchor and shotcrete support system with the different plate and shotcrete such as the pull-out performance of support system, deformation and failure properties of shotcrete was studied and analyzed. Experimental results showed that the relationship curves between elongation and drawing force has three stages, which are elastic, yielding and strengthening. Different plate types have obvious influence on the tensile stiffness during the elastic stage. The steel fiber reinforced concrete spray layer can improve the yield strength of rockbolt under the coupling effect by the support system. The strain at the interface between the initial shotcrete layer and surrounding rock mass is greater than that of the external surface of the resprayed shotcrete layer, though they are equal far away from the rockbolt hole. The shotcrete strain values of steel fiber reinforced concrete is lower than that of plain concrete, and the shotcrete strain values decreases with the improvement of steel fiber content. For shotcrete strain values on the same position, the higher they are the steel fiber content, the lower their strain will be. The failure of plain shotcrete usually begins around of rockbolt hole, when the interfacial stress between the initial shotcrete layer and surround rock is higher than that in the initial shotcrete layer and resprayed shotcrete layer. The steel fiber can effectively improves the toughness, anti-cracking performance and prevent fracture of shotcrete from failure properties.

1 Introduction

In the 1880s, anchor and shotcrete support technology was first applied to the reinforcement of coal mines in North Wales, England. Since the middle and late 20th century, this technology has been widely popularized and promoted in the underground engineering construction in France, Germany, Sweden, Switzerland, Australia, China and other countries (Stillborg 1984). Anchor and shotcrete support technology forms a support system with the joint help of rockbolt, concrete spray layer, plate and surrounding rock mass, which can fully significantly improve the strength and stability of surrounding rock mass (You 2004). In addition, the technology also has outstanding advantages such as simple construction, strong engineering adaptability, and significant saving of engineering materials (Cheng 2005). Anchor and shotcrete support technology has become one of the most economical and effective support methods applied in underground engineering (Nakayama 1987; Kang 2021).

The main function of rockbolt in the anchor and shotcrete support technology is to strengthen deformation resistance of surrounding rock mass and control its deformation, making the surrounding rock mass as a part of the support system. Skrzypkowski determined the quasi-static coefficients for the partially embedded rockbolts by laboratory tests (Skrzypkowski 2021). Chen et al. studied the bolt-anchoring mechanism for bedded rock mass by model test (Chen et al. 2020). Piccinin et al. deduced the theoretical calculation formula of rockbolt pull-out force in anchor and shotcrete support system (Piccinin et al. 2012). Shotcrete play an important arch structure roles in the anchor and shotcrete support system.

Usama et al. investigated the axial behaviour of precast concrete panels with hollow composite reinforcing systems (Usama et al. 2021). Sjölander et al. obtained that the steel fiber reinforced concrete spary layer has the flexible pressure-yielding function in the anchor and shotcrete support system (Sjölander et al. 2020). Su et al. investigated the mechanical performance of tunnel lining with the protection of rock bolts and shotcrete based on the theory of build-up arches (Su et al. 2015). Plates play significant roles during the load transmission between different parts of the support system. Helen et al. investigated the mechanical behavior of end plate connections with prestressed rockbolts by finite element simulations (Helen et al. 2019). Kang et al. studied the influence of plate on the stress field caused by bolt pretension field and its support effect on surrounding rock mass (Kang et al. 2012). Jiang analyzed the influence of the plate on the stress distribution in surrounding rock mass after the pre-stressing of rockbolts based on the FLAC (Jiang 2008). Above researches have vastly perfected the anchor and shotcrete support theory and effectively promoted the massive application of this support technology in engineering.

All the above studies focused on only a certain bearing part or two in the whole anchor and shotcrete support system. Studies on the mechanical behavior of anchor and shotcrete support system under the coupling effect by the plate and shotcrete, as well as the deformation and failure properties of the different shotcrete in the anchor and shotcrete support system with different plate types, are still very limited. Therefore, a series of axial pull-out tests of anchor and shotcrete support system with the different plate and shotcrete were conducted by use of multi-function testing system for the anchor and shotcrete support system. Based on the experimental results, the mechanical behavior of the anchor and shotcrete support system with the different plate and shotcrete such as the pull-out performance of support system, deformation and failure properties of shotcrete was studied and analyzed. The research results can provide reference for the design and construction of anchor and shotcrete support structure in underground engineering.

2 Multi-functional Testing System For Anchor And Shotcrete Support

Due to the limitation of maximum drawing force and test range, commercially available bolt testing machines cannot meet the requirements of the mechanical performance testing of new types of bolts such as high-strength bolts and large-deformation bolts developed based on pressure principle. Meanwhile, they also can not precisely simulate the in-site interaction between bolts and surrounding rock as well as the coupled action between plates and shotcrete. Hence, they are unable to meet the requirement of this study. The authors designed a multi-functional testing system for anchor and shotcrete support, as shown in Fig.1.

2.1 Components of testing system

The test system consists of counter force frame, loading device, measurement device, control system and data acquisition and processing system, as shown in Fig.2.

2.2 Function and Technical Parameters of Testing System

It can provide drawing force as great as 600 kN, and the maximum pull-out stroke is 300 mm. It can simulate the in-site interfacial interaction between the rockbolt and adhesive material, and that between the anchoring body and surrounding rock mass. Moreover, it can also simulate axial/eccentric pull-out property of bolt under the coupled action of plates and shotcrete, and the deformation behaviors of surrounding rock mass and shotcrete. In addition, it can realize the real-time acquisition, dynamic displaying and paragraph preparation of test data.

The sensor of BL100-V-1000 was used to measure the displacement in the pull-out test and the electrical resistance strain pressure sensor of BLR-1/50t was used to monitor the axial force in the test, as shown in Fig. 2, and the eight-channel data acquisition system software of BL800-E8 was used to record the data of displacement and axial force in the test. According to the Building Anchor Bolt Test Method (China Code DG/TJ08-003-2013), the loading rate was 10 kN/min and the loading should be kept continuous and uniformly.

3 Axial Pull-out Test Of Anchor And Shotcrete Support System

3.1 Testing Materials

Cast-in-situ shotcrete were used in this study. The principal raw materials of the shotcrete were cement, aggregate, steel fibre and water. The cement used was 32.5# ordinary Portland cement produced by Henan Jiaozuo Jiangu Cement Co., LTD. Coarse aggregates were gravels with diameters ranging from 20 to 35 mm. The gravels were well graded, clean, dry and had crush indexes between 7.9% and 8.1%. Fine aggregates were river sand with high quality. The fineness modulus of sand was 2.63, with the maximum particle size lower than 5 mm. The sand was well graded, clean and dry. The hooked steel fiber content was added (by volume) to the steel fiber concrete. According to the research findings (Zhao 2017), when the steel fiber content in concrete is greater than 2.0% (volume ratio), the workability of concrete is significantly affected, and the construction quality of engineering cannot be guaranteed. Further, based on the accumulation of the research group, the steel fiber content in the steel fiber reinforced concrete spray layer is 0.5 %, 1.0 %, 1.5 % (volume ratio). Plain concrete and steel fiber reinforced concrete with strength values of C20, were prepared according to calculation. The prepared concretes were poured into shotcrete in detachable special mould made of Q235 steel plates. 9 pieces of C30 concrete substrate blocks with dimension of 500×500×300 mm^3 were poured in mould to simulate surrounding rock mass.

Left-handed ribbed high-strength bolts produced by Jiaozuo coal company of HNCC were selected in this study. The bolts were made of MG400 bolt steel, with 3 m in length and 22 in diameter. Their yield strength was 400 MPa and ultimate tensile strength was 540 MPa. During testing, three types of plates, flat plate, butterfly plate and new-type plate, were used, as shown in Fig. 3. Among them, the butterfly plate can use its own round drum shell form to achieve pressure-yielding function.

3.2 Testing Method and Scheme

(1) Preparation method of the anchor and shotcrete support system: The shotcrete used in the pull-out tests had a dimension of 500×500×150 mm^3 (Liu et al. 2010), with a hole of 50 mm in diameter reserved at the center as the anchoring reserved hole for rockbolt. During pouring the shotcrete, an initial shotcrete layer with a thickness of 60 mm was firstly poured and then a resprayed shotcrete layer with a thickness of 90 mm was poured. When pouring the resprayed shotcrete layer, a square hole with a dimension of 160×160 mm^2 was reserved at the center adjacent to the initial shotcrete layer, in order to install the plate. After the installation of the plate, concrete was poured to both inside and outside the square hole to a certain thickness at the same time. After that, the wood die for the square hole was removed and the square hole was poured to the designed thickness and vibrated. The pouring process of the shotcrete is illustrated in Fig. 4.

(2) Test method of bolt pull-out in the anchor and shotcrete support system: The prepared detachable die was firstly fixed at one end of the test system. Then, substrate blocks and shotcrete were placed inside the die and fixed. The substrate blocks and shotcrete were constrained by the die. Bolts were then anchored to the drawing end and the shotcrete end through the reserved hole. The drawing end was the anchored end and the spherical anchorage with 21 mm in diameter produced by Henan Yujian Mining Technology Co., LTD was used. After the installation of the anchor and shotcrete support system, tests were conducted under specific conditions, with the pull-out load and bolt elongation recorded. When the loading system reached its maximum stroke, the shotcrete was seriously damaged or the bolt tail was failured, tests were ended. In this study, 9 sets of pull-out tests with three types of plates and two kinds of shotcretes (plain and steel fiber reinforced concrete) were carried out. To analyze the strain features of different sites at the interface between the initial shotcrete layer and surrounding rock mass, the interface between the initial shotcrete layer and resprayed shotcrete layer, the external surface of the resprayed shotcrete layer during testing, SZ120-50AA resistance strain gages were pasted on these sites.

4 Test Results Analysis

4.1 Relationship Curves of Drawing Force and Elongations

Relationship curves between the drawing force and elongation with three types of plates and two kinds of shotcretes (plain and steel fiber reinforced concrete) are shown in Fig. 5 and Fig. 6, respectively. The mechanical behavior of the anchor and shotcrete support system with the steel fiber reinforced concrete spray layers, as shown in Table 1.

According to Fig. 5, Fig. 6, Table 1 and related test data, we can find that:

(1) Under different plate/shotcrete combination conditions, the relation curves between the drawing force and elongation present similar variation trends. By taking the combined influence of three types of plates and two kinds of shotcretes (plain and steel fiber reinforced concrete), the pull-out process can be divided into three stages with obvious features, which are elastic (OA stage), yield (AB stage) and hardening (BC stage).

(2) The different plate types has significant influence on the tensile stiffness at the elastic stage. In the condition of plain concrete, when flat plates, butterfly plates and new-type plates are used, the tensile stiffness is 8.83 MN/m, 5.59 MN/m and 4.71 MN/m, respectively. This is mainly attributed to that the lack of pressure-yielding function of the flat plate. As for the steel fiber reinforced concrete, with the same steel fiber content, the pull-out curves slope of the new-type plate is lesser than those of the butterfly plate and flat plate at the elastic stage. This means that the new-type plate can extend the elastic stage of pull-out curves. Thus, it is indicated that the flat plate is not beneficial to the full development of the elastic deformation stage of the anchor and shotcrete support system, thereby affects the controllable release of surrounding rock during the early excavation of tunnels or roadways.

(3) In the condition of plain concrete, when flat plates, new-type plates and butterfly plates are used, the yield platform widths is 41 mm, 47 mm and 50 mm, and the yield strength of bolt is 175 kN, 181 kN and 181 kN, respectively. This shows that the pressure-yielding and deformation resistance of butterfly plate and new-type plate are higher than that of flat plate in the anchor and shotcrete support system. As for the steel fiber reinforced concrete, when flat plates are used, the yield platform widths in the anchor and shotcrete support system is not obviously affected by the steel fiber content, and the bolt yield strength are all 181 kN. Compared with plain concrete, the yield strength of bolt is increased by 4%. When butterfly plates are used, the pull-out curves slope of steel fiber reinforced concrete in curves elastic stage is greater than plain concrete, and the yield platform widths is almost similar. When new-type plates are utilized, the bolt yield strength gradually increases with the accession of steel fiber content. This shows that the steel fiber can improve the yield strength of bolt and slope of curves elastic stage.

4.2 Shotcrete Strain in the Pull-out Process under Different Plate and Shotcrete

(1) Analysis of shotcrete strain under different plate

According to test data, draw out 20 mm outside the rockbolt hole at the interface between initial shotcrete layer and resprayed shotcrete layer, 70mm outside the rockbolt hole at the external surface of resprayed shotcrete layer, 20 mm outside the rockbolt hole at the interface between initial shotcrete layer and surrounding rock mass, and 70 mm outside the rockbolt hole at the interface between initial shotcrete layer and surrounding rock mass of relation curves between the shotcrete strain and drawing force (The steel fiber content is 1.0%.), as shown in Fig.7. Since the variation tendencies of shotcrete strain corresponding to steel fiber reinforced concrete spray layer with 0.5% and 1.5% steel fiber content, are similar to that of 1.0% steel fiber content, only the 1.0% steel fiber content is discussed here. [**Note**: The above 4 different positions are denoted as: M1, M2, M3 and M4.]

According to Fig. 7 and related test data, we can find that:

1) When butterfly plates are used, the initial strain around the rockbolt holes at the interface between the initial shotcrete layer and the resprayed shotcrete layer, and the interface between the initial shotcrete layer and the surrounding rock mass is lower than when flat plates or new-type plates are used. This is attributed to that at the early stage of loading, the center of the butterfly plate cannot contact with the

initial shotcrete layer, and with the loading increasing, the butterfly plate deforms and contacts the initial shotcrete layer until the test ends. Thus, it is demonstrated that the butterfly plate has the function of pressure-yielding. 2) When new-type plates are adopted, the slope of the strain-drawing force curve around the rockbolt hole at the external surface of the resprayed shotcrete layer experiences a sharp increase. This is caused by that with the load increasing, the new plate deforms and introduces pressure on the shotcrete, which hinders the further increase of strain. The new plate presents the property of limiting the exorbitant deformation of shotcrete. 3) The interface between the initial shotcrete layer and surrounding rock mass has strain slightly greater than that of the interface between the initial shotcrete layer and resprayed shotcrete layer. The strain at the interface between the initial shotcrete layer and surrounding rock mass is greater than that of the external surface of the resprayed shotcrete layer, though they are equal far away from the rockbolt hole. This phenomenon also explains why the shotcrete often starts to break around the rockbolt hole during pull-out tests under the coupled action of plates and shotcrete in anchor and shotcrete support system.

(2) Analysis of shotcrete strain under different shotcrete

On the basis of test data, the relation curves between the shotcrete strain and drawing force (M1-M4) with butterfly plate and two kinds of shotcretes (plain and steel fiber reinforced concrete) are displayed in Fig.8. Since the variation tendencies of shotcrete strain corresponding to different combination conditions between new-type plate and flat plate with plain shotcrete and steel fiber reinforced concrete, are similar to that of butterfly plate, only the butterfly plate is discussed here.

Some results drawn from Fig.8 are as fellows: 1) The shotcrete strain increases with the accession of the drawing force. Around the rockbolt hole, the shotcrete is obviously yielded at the late loading stage. For strain values on the same position, the higher they are the steel fiber content, the lower their strain will be. 2) When the drawing force is small, the slope of relationship curves between the drawing force and shotcrete strain increases with the improvement of steel fiber content. This is mainly attributed to that the steel fiber increases the toughness of concrete. 3) The strain of steel fiber reinforced concrete is lower than that of plain concrete, and the strain values decreases with the improvement of steel fiber content. This shows that steel fiber reinforced concrete significantly improves the anti-cracking performance of concrete. 4) The strain values of steel fiber reinforced concrete spray layer with 1.0% and 1.5% steel fiber content is similar. This indicates that the strain values will not decrease infinitely with the increase of steel fiber content.

4.3 Failure properties comparison of different shotcrete

The failure properties of different shotcrete, as shown in Table 2. Since the failure properties of steel fiber reinforced concrete spray layer with 0.5% and 1.5% steel fiber content, are similar to that of 1.0% steel fiber content, only the 1.0% steel fiber content is discussed here.

(1) In the condition of plain concrete, the failure properties of the flat plate and butterfly plate are similar. The cracks extend from the vicinity of rockbolt hole in the initial shotcrete layer to the border as well as

the resprayed shotcrete layer, until the shotcrete gets failure. The crack pattern is outward radial with the rockbolt hole as the center point. Under the coupled action of new plates and plain shotcrete, the failure properties are cracks radiating outward in the initial shotcrete layer with the rockbolt hole as the center point. The cracks in the resprayed shotcrete layer run through along the same direction, which is attributed to that the plate types with the drawing force increasing and introduces pressure on the shotcrete to hinder the generation of cracks. Thus, it is indicated that the new plate has the function to prevent shotcrete fracturing.

(2) As for the steel fiber reinforced concrete, the failure properties of the flat plate, butterfly plate and new-type plate are similar. The cracks extend from the vicinity of rockbolt hole in the initial shotcrete layer, and the cracks in the resprayed shotcrete layer are very small and almost invisible to the naked eye. At the end of pull-out tests, the shotcrete was not obviously damaged, and the integrity is better. Failure properties indicates that the steel fiber makes the shotcrete better tough and obviously improves the anti-cracking of shotcrete.

5 Conclusions

Based on axial pull-out performance tests of anchor and shotcrete support system with three types of plates and two kinds of shotcretes (plain and steel fiber reinforced concrete) conducted by use of the multi-functional testing system some conclusions can be drawn as follows:

(1) The relation curves between drawing force and elongation under the coupling effect by three types of plates and two kinds of shotcretes (plain and steel fiber reinforced concrete) can be divided into three stages with obvious features, which are elastic, yield and strengthening. The influence of different plate types on the bolt yield strength is very limited, but has significant effect on the tensile stiffness at the elastic stage.

(2) In the condition of plain concrete and axial pull-out action, the pressure-yielding and deformation resistance of butterfly plates and new-type plates are higher than that of flat plates in the anchor and shotcrete support system. As for the steel fiber reinforced concrete, the yield platform widths of anchor and shotcrete support system is not obviously affected by the steel fiber content. The butterfly plate and new-type plate show better function of pressure-yielding.

(3) When butterfly plates are used, the initial strain around the rockbolt holes at the interface between the initial shotcrete layer and the resprayed shotcrete layer, and the interface between the initial shotcrete layer and the surrounding rock mass is lower than when flat plates or new-type plates are used. The strain of steel fiber reinforced concrete is lower than that of plain concrete, and the strain values decreases with the improvement of steel fiber content. For strain values on the same position, the higher they are the steel fiber content, the lower their strain will be.

(4) In the condition of plain concrete, the cracks are outward radically distributed with rockbolt hole as center points; the cracks extend from the vicinity of rockbolt hole in the initial shotcrete layer to the border

as well as the resprayed shotcrete layer, until the shotcrete gets failure. As for the steel fiber reinforced concrete, the shotcrete was not obviously damaged, and the integrity is better. Failure properties indicates that the steel fiber makes the shotcrete better tough and obviously improves the anti-cracking of shotcrete.

Declarations

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Data Availability The data used to support the findings of this study are included and showed within the article.

Compliance with Ethical Standards

Competing interests The authors declare that there is no conflict of interest regarding the publication of this paper.

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Tables

Table 1 The mechanical behavior of the anchor and shotcrete support system with the steel fiber reinforced concrete spray layers

Plate types	Steel fiber content	Yield strength (kN)	Yield platform width (mm)	Slope of elastic stage (MN/m)
Flat plate	0.5%	181	43	11.10
	1.0%	181	44	8.63
	1.5%	181	43	8.53
Butterfly plate	0.5%	181	58	10.10
	1.0%	183	60	10.10
	1.5%	186	59	9.50
New-type plate	0.5%	181	46	4.75
	1.0%	182	48	5.67
	1.5%	183	47	6.78

Due to technical limitations, table 2 is only available as a download in the Supplemental Files section.

Figures

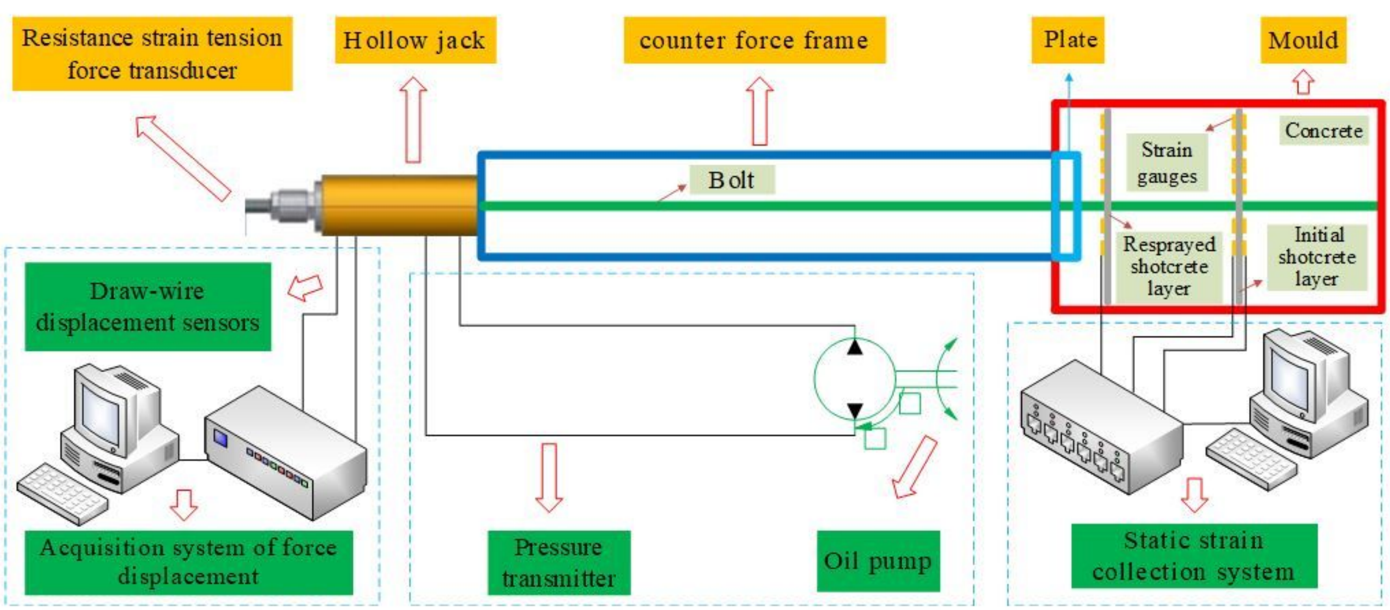

Figure 1

Multi-functional testing system for anchor and shotcrete support

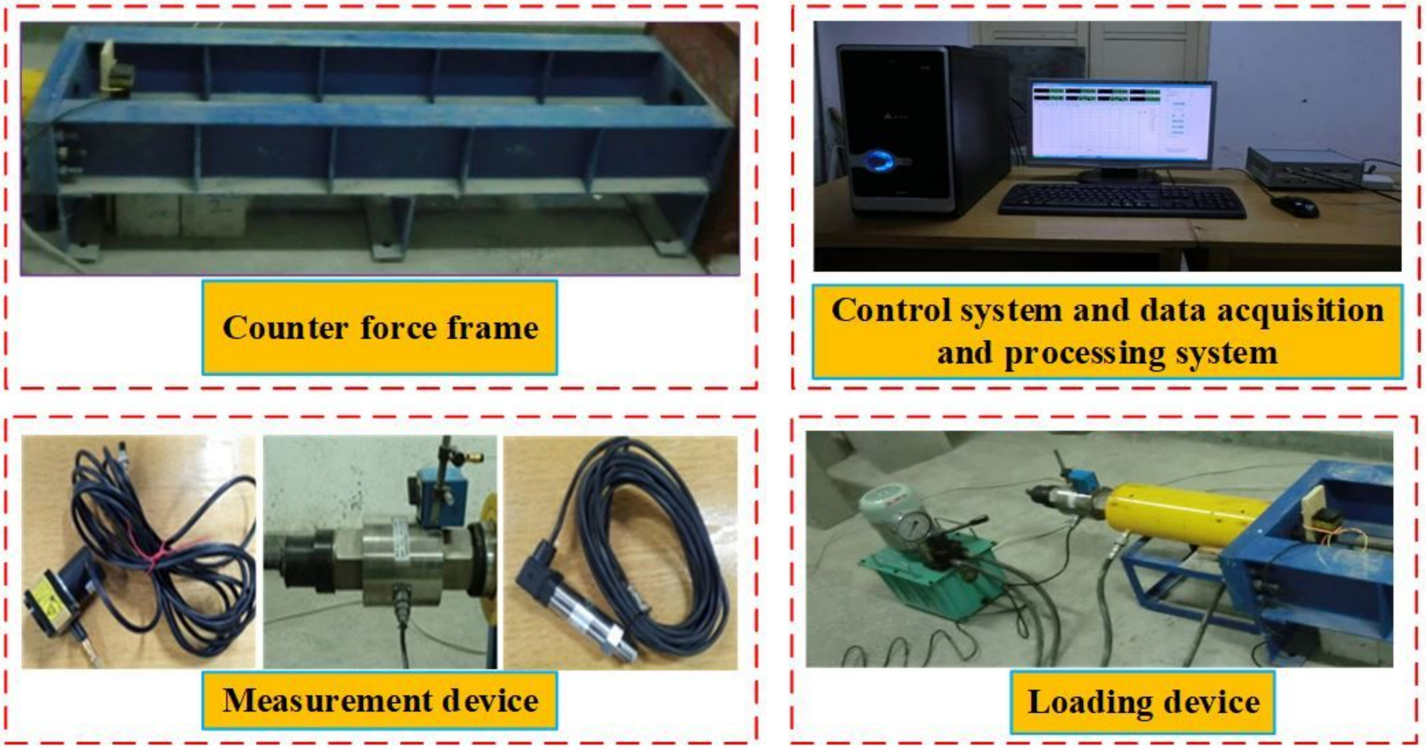

Figure 2

Components of testing system

Figure 3

Plate styles used in pull-out tests

Figure 4

Pouring process of the resprayed shotcrete layer

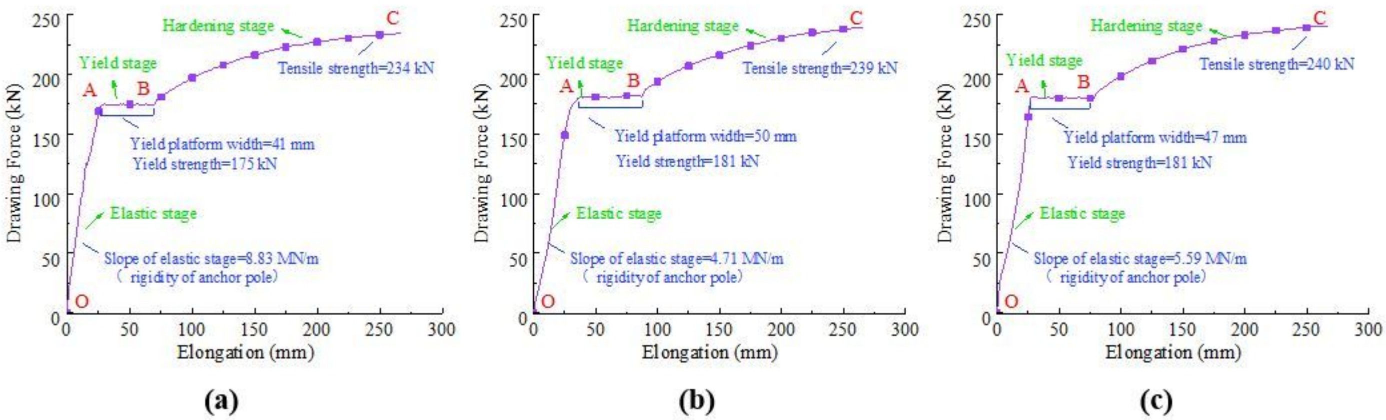

Figure 5

Relation curves between the drawing force and elongation (plain concrete). a Flat plate; b Butterfly plate; c New-type plate

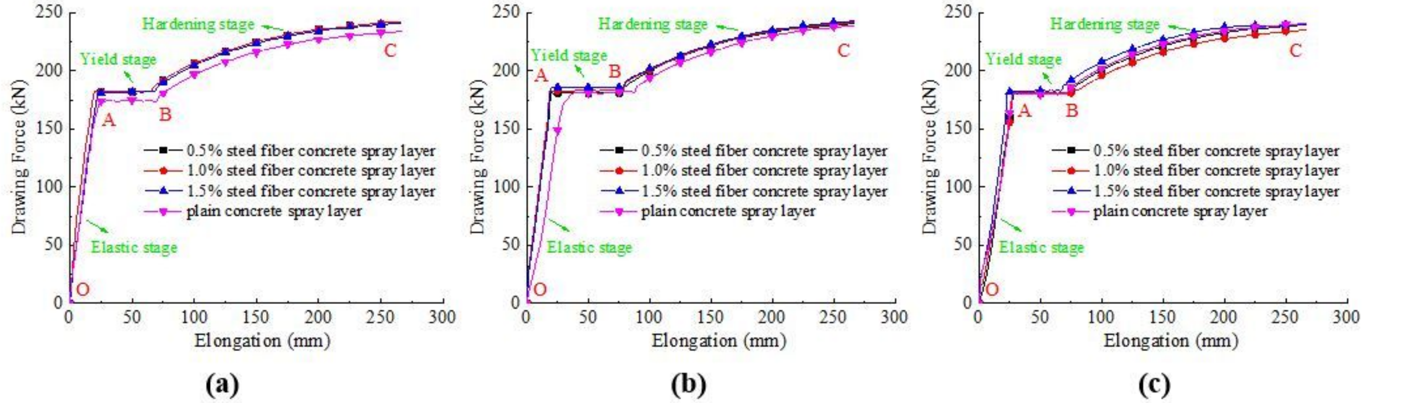

Figure 6

Relation curves between the drawing force and elongation (steel fiber reinforced concrete). a Flat plate; b Butterfly plate; c New-type plate

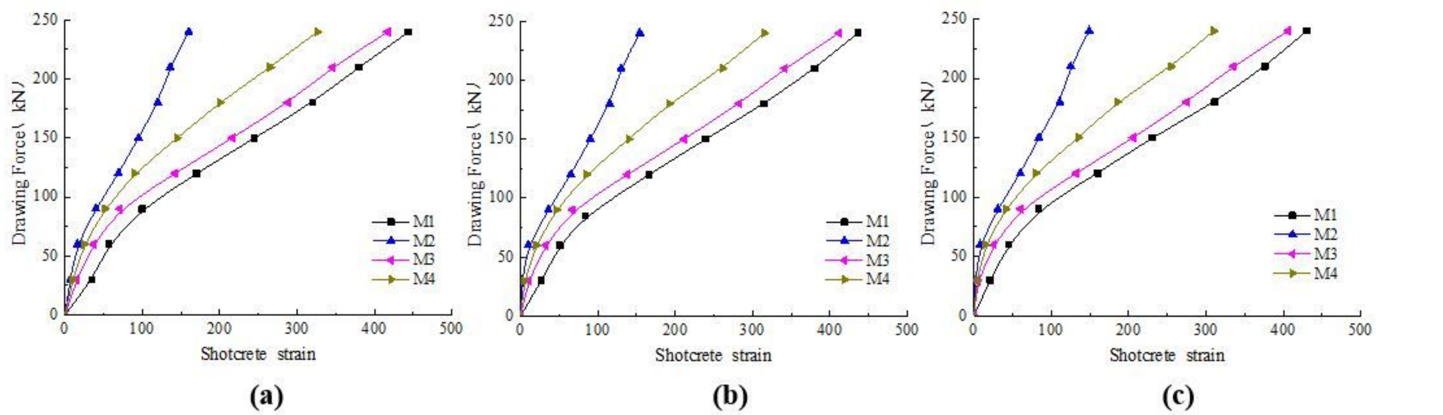

Figure 7

Relation curves between the drawing force and shotcrete strain. a Flat plate; b Butterfly plate; c New-type plate

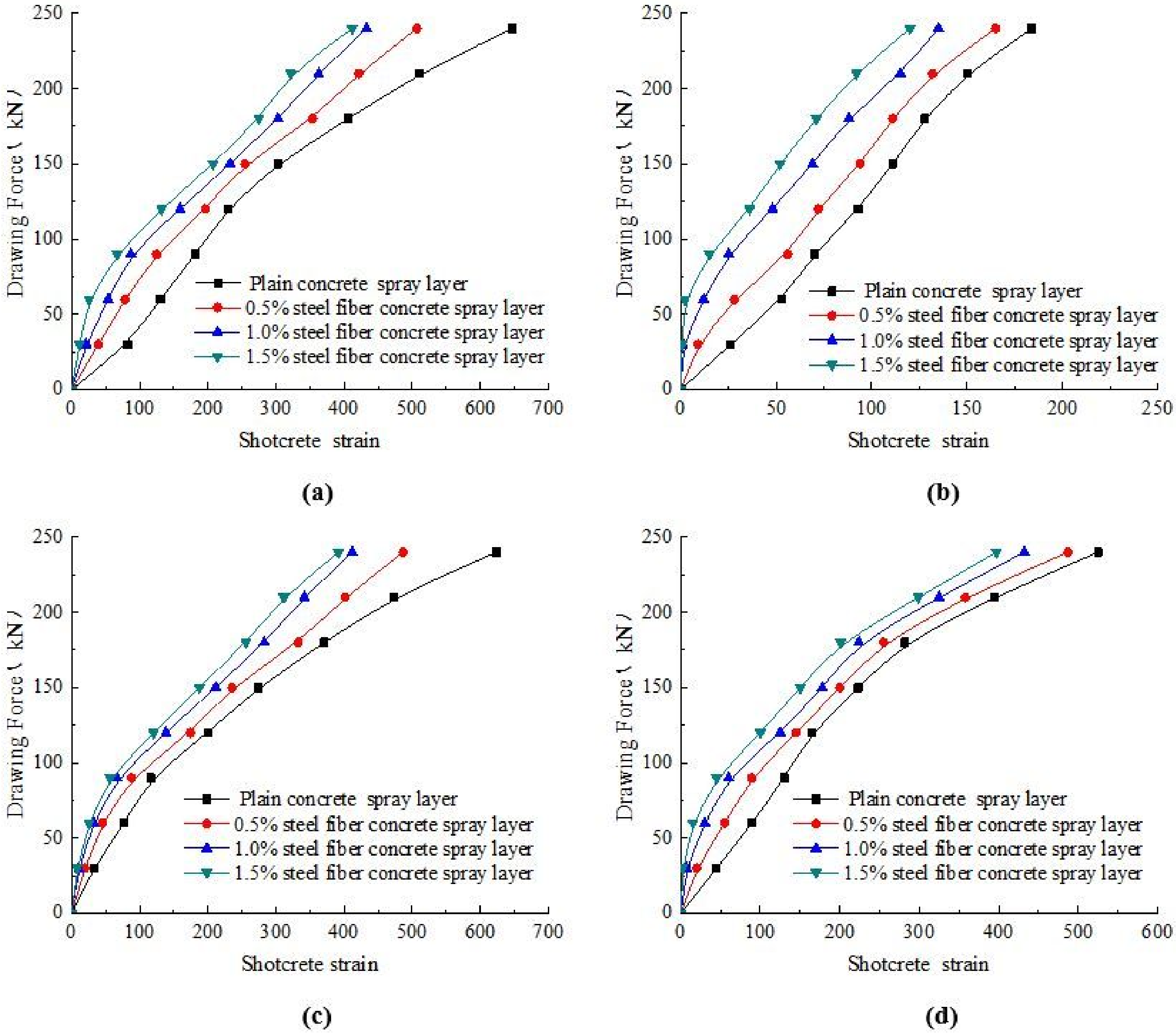

Figure 8

Relation curves between the bolt drawing force and shotcrete strain. a-d: M1-M4

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table2Failurepropertiesofdifferentshotcrete.docx