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Experimental Study on Bolt Pull-Out Property Coupled by Plate and Shotcrete

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ABSTRACT
Based on a self-developed multi-function bolt mechanical test system, axial pull-out loads were applied on same bolts under the different conditions, combining with a flat plate, a butterfly plate, a new-type plate and three kinds of shotcrete(C15, C20 and C25 plain concrete). Experimental results showed that the relationship between bolt elongation and drawing force has three stages, including elastic, yielding and strengthening. The strength of shotcrete lining has an obvious influence on the bolt stiffness during the elastic stage i.e. the strengthening of the concrete leads to the increase of bolt stiffness. The strength and width of the yield platform of the bolt reach the maximum for the butterfly plate and the yield plate with C20 plain concrete lining. The butterfly plate and the new-type plate both have yield functions, and the latter one can effectively prevent the damage of shotcrete. The damage of shotcrete lining usually begins around the drill holes, when the interfacial stress between the initial shotcrete lining and surround rock is higher than that in the initial lining and secondary lining. With the new-type plate used, the cracks in the secondary lining cut through along the same direction.

KEY WORDS: Pull-Out Test; Coupling Effect; Strain; Fracture Morphology

1. INTRODUCTION

Anchor bolt-spray has become one of the most economic and effective support methods applied in underground projects (WANG Jin-hua, 2007; Anders Ansell, 2005). The main function of bolts in the bolting and shotcreting technology is to improve deformation resistance of surrounding rock and control the rock deformation, making the surrounding rock as a part of the support system. In recent years, many scholars around the world have carried out massive and in-depth theoretical researches about the bolts (HE Manchao et al, 2014; ZHAO Tong-bin et al, 2011; M.Cai and D.Champaigne, 2012). Shotcrete lining plays an important structural roles in the combined support system. Shi Ling analyzed the functions of shotcrete lining under the stress-control and the structure-control mode (SHI Ling, 2011). Wen Jingzhou developed the bearing model of the surrounding rock-shotcrete lining structure (WEN Jingzhou et al, 2011). Fang Shulin et al monitored the stress state of the post-shot concrete in a roadway (FANG Shu-lin et al, 2012). Xiang Wei et al. investigated the deformation law and interaction mechanism of surrounding rock and shotcrete lining under freeze-thaw cycles (XIANG Wei et al, 2011). Plates play significant roles during the load transmission between different parts of the support system. Jiang Tieming analyzed the influence of the plate on the stress distribution in the surrounding rock after the pre-stressing of bolts based on the FLAC (JIANG Tieming, 2008). Wang Jianzhi et al. studied the influence of plates on the internal stress distribution of bolts (WANG Jianzhi et al, 1989). Kang Hongpu et al. studied the influence of a plate on the bolt pre-stress field and its support effect on the surrounding rock. Above-mentioned researches have vastly perfected the anchor bolt-spray support theory and effectively promoted the massive application of this technology in engineering.

All the aforementioned studies focused on only a certain bearing part or two in the whole bolt-spray support system. Studies on the interaction between plate and shotcrete, as well as the bolt stress behavior under the coupled action of them, are still very limited. Therefore, a self-developed multi-function bolt mechanical test system was adopted to conduct pull-out tests of the same type of bolts under different combination conditions between plate types and plain shotcrete linings with various strength values. Based on the experimental results, the bolt stress state under the coupled action of plates and shotcrete linings, and the deformation and fracture behaviors of shotcrete linings were discussed.

2. TEST SYSTEM AND METHOD

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2.1 Test system

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 cannot precisely simulate the in-site interaction between bolts and surrounding rock as well as the coupled action between plates and shotcrete linings. Hence, they are unable to meet the requirement of this study. The authors designed a multi-function bolt mechanical test system, as shown in Fig.1. The test system consists of counter force frame, anchorage, loading device, measurement device, control system and data acquisition and processing 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 bolt and adhesive material, and that between the anchoring body and surrounding rock. Moreover, it can also simulate axial/eccentric pull-out property of bolt under the coupled action of plates and shotcrete linings, and the deformation behavior of surrounding rock and shotcrete lining. In addition, it can realize the real-time acquisition, dynamic displaying and paragraph preparation of test data.

Fig.1. The self-developed multi-function bolt mechanical test system

2.2 Test materials

Cast-in-situ shotcrete linings were used in this study. The principal raw materials of the shotcrete linings were cement, aggregate 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. Plain concretes with strength values of C15, C20 and C25, were prepared according to calculation. The prepared concretes were poured into shotcrete linings in detachable special mould made of Q235 steel plates. 9 pieces of C30 concrete substrate blocks with dimension of 500 mm ×500 mm ×300 mm were poured in mould to simulate surrounding rock.

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 is 400 MPa and ultimate tensile strength is 540 MPa. During testing, three types of plates, flat plate, butterfly plate and new-type plate, were used, as shown in Fig. 2.

(*a*) flat plate (*b*) butterfly plate and (*c*) new-type plate.

Figure 2. Plates used in tests

2.3 Test method and scheme

(1) Preparation method of the plate and shotcrete lining system: The shotcrete lining used in the pull-out test had a dimension of 500 mm × 500 mm × 150 mm(JIANG Tieming, 2008), with a hole of 50 mm in diameter reserved at the center as the anchoring reserved hole for bolts. During pouring the shotcrete lining, an initial lining with a thickness of 60 mm was firstly poured and then a secondary shotcrete lining with a thickness of 90 mm was poured. When pouring the secondary shotcrete lining, a square hole with a dimension of 160 mm ×160 mm was reserved at the center adjacent to the initial lining, 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 lining is illustrated in Fig. 3.

Figure 3. Pouring process of the secondary shotcrete lining, (a) before pouring, (b) after pouring.

(2) Test method of bolt pull-out under the coupled action of plates and shotcrete linings: The prepared detachable die was firstly fixed at one end of the test system. Then, substrate blocks and shotcrete linings were placed inside the die and fixed.

The substrate blocks and shotcrete linings were constrained by the die. Bolts were then anchored to the drawing end and the shotcrete lining 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 shotcrete-bolt 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 lining was seriously damaged or the bolt tail was fractured, tests were ended. In this study, 9 sets of pull-out tests with 3 kinds of plates and 3 strength grades of shotcrete linings were carried out. To analyze the strain features of different locations at the contact interface between the initial lining and surrounding rock, the contact interface between the initial lining and the secondary lining, the external surface of the secondary lining during testing, SZ120-50AA resistance strain gages were pasted on these locations.

3. RELATIONSHIP CURVES OF DRAWING FORCE AND ELONGATIONS

Relationship curves between the bolt drawing force and elongation under the different combination conditions of plates and shotcrete linings are shown in Fig. 4.

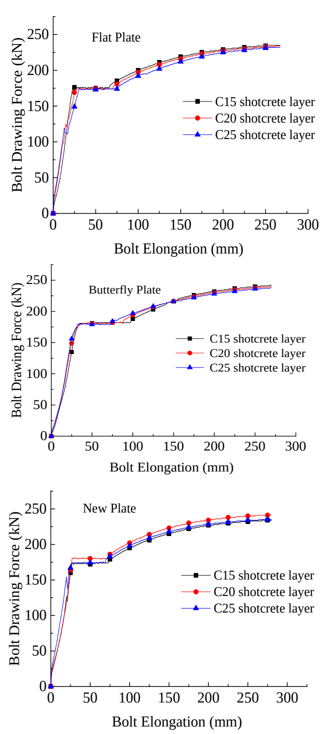
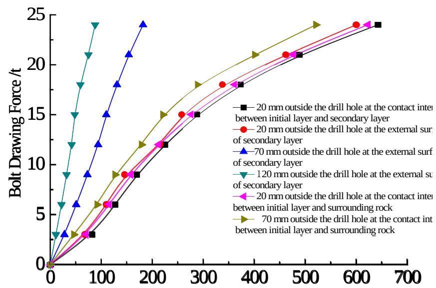


Figure 4. Bolt drawing force-elongation relation curves under different combination conditions of plates and shotcrete linings

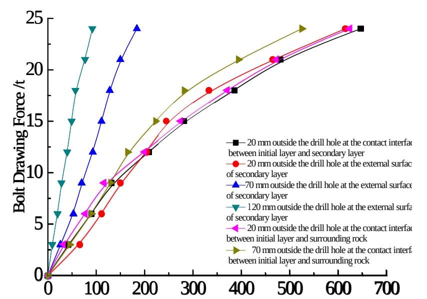
According to Fig. 4 and related test data, we can find that:(1)Under different plate/lining combination conditions, the relation curves between the bolt drawing force and elongation present similar variation trends. By taking the combined influence of plates and shotcrete linings, the bolt drawing process can be divided into three stages with obvious features, which are elastic, yield and hardening. (2)With the same plate type, the intrinsic strength of shotcrete lining has limited influence on the bolt yield strength. The shotcrete lining strength has significant influence on the bolt stiffness at the elastic stage, at which the bolt stiffness increases with the improvement of shotcrete lining strength. When butterfly plates are used, the bolt stiffness increases from 4.45 MN/m to 4.86 MN/m when the shotcrete strength increasing from C15 to C25. When flat plates are used, the bolt stiffness increases from 6.42 MN/m to 9.22 MN/m, and the bolt stiffness increases from 5.89 MN/m to 7.89 MN/m when new-type plates are utilized. This is mainly attributed to that the influence of the shotcrete in the early bearing stage of the shotcrete-bolt support system is more dominant. In addition, above test results can also explain the reason why exorbitant shotcrete lining strength is not beneficial to the release of surrounding rock pressure and the play of the intrinsic bearing capacity of surrounding rock in shotcrete-bolt support systems. (3)With the same shotcrete strength, the curve slope of the flat plate is greater than those of the butterfly plate and new-type plate at the elastic stage, due to the lack of pressure relief function of the flat plate. Thus, it is indicated that the flat plate is not beneficial to the full development of the elastic deformation stage of the shotcrete-bolt support system, thereby affects the controllable release of surrounding rock during the early excavation of tunnels or roadways. (4)When flat plates are used, the bolt yield strength under the coupled influence of plates and shotcrete linings is not obviously affected by the shotcrete lining strength, and the widths of the yield platforms are all 42 mm. However, after the bolt is yielded, the elongation slightly increases with the improvement of shotcrete lining strength. (6)When butterfly plates are used, the elongation and yield strength of bolts during yielding are almost the same. But the yield platform width gradually increases with the reduction of shotcrete lining strength. Based on calculation, the yield platform width of the C15 shotcrete strength is 1.24 times of that of C20 and 1.219 times of that of C25. Hence, it is implied that the increase of shotcrete lining strength when butterfly plates are used, is not beneficial to bolt yielding.(7)When new-type plates are utilized, under the coupled action of plates and shotcrete linings, the bolt yield strength firstly increases and then decreases with the increase of shotcrete lining strength. The bolt yield platform widths and elongations during yielding are almost similar.

4. SHOTCRETE LINING STRAIN UNDER THE COUPLED ACTION OF PLATE AND SHOTCRETE

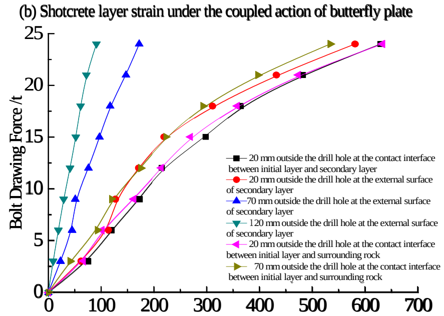
The relation curves between the shotcrete lining strain and bolt drawing force under different combination conditions between C20 plain shotcrete and three types of plates are displayed in Fig.5. Since the variation tendencies of shotcrete lining strain corresponding to different combination conditions between C15 and C25 plain shotcrete with different types of plates, are similar to that of C20 plain shotcrete, only the C20 plain shotcrete lining is discussed here.



(a) Shotcrete layer strain under the coupled action of flat plate



(b) Shotcrete layer strain under the coupled action of butterfly plate



(c) Shotcrete layer strain under the coupled action of new plate

Figure 5.Relation curves between the shotcrete lining strain and bolt drawing force

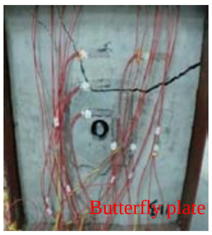
Some results drawn from Fig.5 are as fellows: (1) The shotcrete lining strain increases with the increase of the bolt drawing force. Around the drill hole, the shotcrete lining is obviously yielded at the late loading stage. (2) For strain gages on the same lining, the further they are away from the drill hole, the lower their strain will be. This phenomenon also explains why the shotcrete lining often starts to break around the drill hole during pull-out tests under the coupled action of plates and shotcrete linings.(3)The contact interface between the initial lining and surrounding rock has strain slightly greater than that of the interface between the initial lining and secondary lining, even their distances to the drill hole are the same. The strain at the contact interface between the initial lining and surrounding rock is greater than that of the external surface of the secondary lining, though they are equal far away from the drill hole. Thus, it is indicated that the stress at the contact interface between the initial lining and the surrounding rock is greater than those at the contact interface between the initial lining and the secondary lining, and at the external surface of the secondary lining. (4)When butterfly plates are used, the initial strain around the drill holes at the contact interface between the initial lining and the secondary lining, and the contact interface between the initial lining and the surrounding rock is lower than those at the same positions when flat plates or new-type plates are used. But the strain will gradually increase to the same value. This is attributed to that at the early stage of loading, the center of the butterfly plate cannot contact with the initial lining, and with the loading increasing, the butterfly plate deforms and contacts the initial lining until the test ends. Thus, it is demonstrated that the butterfly plate has the function of pressure relief. (5)When new-type plates are adopted, the slope of the strain-drawing force curve around the drill hole at the external surface of the secondary lining experiences a sharp increase. This is caused by that with the increasing load, the new plate deforms and introduces pressure on the shotcrete lining, which hinders the further increase of strain. The new plate presents the property of limiting the exorbitant deformation of shotcrete lining.

5. SHOTCRETE FRACTURE PROPERTY

Plain concrete possesses remarkable brittleness, which becomes more obvious with the increase of strength. The brittleness of plain concrete in bolting and shotcreting support system mainly reflects in this mode, that is, the micro cracks on the plain shotcrete lining surface rapidly develops wider, deeper and longer until cutting through the shotcrete lining surface and fully fracturing the shotcrete lining. By taking the C20 plain shotcrete lining as an examples, the fracture morphologies under the coupled action of plates and shotcrete linings after bolt axial pull-out tests are shown in Fig. 7.

(*a*) Front side

(*b*) Back side



(*a*) Front side

(*b*) Back side

(*a*) Front side

(*b*) Back side

Figure 7. Fracture morphologies of C20 plain shotcrete linings

As demonstrated in Fig.7, the fracture modes of the flat plate and butterfly plate are similar. The cracks extend from the vicinity of drill hole in the initial lining to the border as well as the secondary lining, until the shotcrete lining gets fractured. The crack pattern is outward radial with the drill hole as the center point. Under the coupled action of new plates and plain shotcrete linings, the fracture morphology is cracks radiating outward in the initial lining with the drill hole as the center point. The cracks in the secondary lining run through along the same direction, which is attributed to that the plate deforms with the increasing drawing force and introduces pressure on the shotcrete linings to hinder the generation of cracks. Thus, it is indicated that the new plate has the function to prevent shotcrete lining fracturing.

6. CONCLUSIONS

Based on axial pull-out of bolt tests conducted on the self-developed multi-function bolt mechanical test system with three types of plates combining with C15, C20 and C25 plain shotcrete linings, a couple of conclusions can be drawn:

(1) The relation curves between bolt drawing force and elongation under different combination conditions of plates and shotcrete linings can be divided into three stages with obvious features, which are elastic, yield and strengthening. The influence of shotcrete strength on the bolt yield strength is very limited, but has a significant effect on the bolt stiffness at the elastic stage, during which the bolt stiffness increases with the increase of shotcrete strength.

(2) Under the condition that flat plates are used, the bolt yield strength is not obviously affected by the shotcrete lining strength, but bolt elongation expands slightly with the shotcrete strength increasing after yielding. When butterfly plates are used, the bolt yield platform width increases with the reduction of shotcrete strength. As for the new-type plate condition, the bolt yield platform width and the elongation to yield are similar. The butterfly plate and new-type plate are revealed to have the function of pressure relief

(3) The shotcrete lining strain increases with the increasing drawing force, and the shotcrete linings present obviously yielding features at the late loading stage. The shotcrete lining often starts to break around the drill hole. The stress at the contact interface between the initial lining and surrounding rock is greater than those at the contact interface between the initial and secondary linings, and at the external surface of the secondary lining.

(4) When flat plates or butterfly plates are used, the cracks are radically distributed outward with drill holes at the center points. As for the new-type plate, the fracture morphology is cracks radiating outward in the initial lining with the drill hole at the center point, while cracks cut through along the same direction in the secondary lining. Thus, a certain degree of layer-fracture resistance of the new-type plate is revealed.

7. ACKNOWLEDGEMENTS

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