MSc Thesis

Study on the shear mechanical behaviour of full-grouted anchor cable

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Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet.”

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Abstract

This thesis investigates the influence of different factors on the shear mechanical properties of full-length grouted anchor ropes through laboratory tests, numerical simulations and theoretical analyses to reveal the interaction between anchor ropes and surrounding rock and the anchoring mechanism for jointed rock masses. Indoor anchor cable shear tests were carried out using self-designed double shear test equipment to analyze the macroscopic characteristics of anchor cable fracture and test block damage. The changes of the anchor cable axial force, shear force and shear displacement during the shear process were recorded. The effects of preload, test block strength and cable type on the shear performance of full-length grouted anchor ropes were also analysed. The results of the numerical simulation are used to analyse the force characteristics and the interaction between the anchor cable and the surrounding rock mass. On the basis of the theoretical analysis, it is considered that the anchoring effect of the anchor cable on the misalignment of the surrounding rock is mainly divided into two parts: the lateral and axial restraint effects, revealing the inner mechanical mechanism of the anchorage of the full-length grouted anchor cable on the jointed rock body

Keywords: full-length grouted anchor cable, double shear test, jointed rock mass, anchorage mechanism

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1 Introduction

1.1 Background

As the main energy resource of China, coal has an important economic and strategic position. It is the "ballast stone" for the stable supply of national energy and security. It is widely used in the production process of power generation, iron and steel, chemical industry, building materials and other important industries, and is an important energy source and industrial raw material to support the country's economic development. At the same time, coal is also the most important part of China's energy structure, occupying a dominant position. In China's economic development, coal, as a basic energy source, has an important role in stable supply. The protection and rational use of coal resources by the state is crucial to ensure national energy security and sustainable economic development. As the demand for coal grows year by year, the upgrading and transformation of the coal industry has become an important task in China's current energy development. However, the depletion of shallow coal resources has led to coal mining gradually into the deep part. The deep tunnel has characteristics of higher ground stress, large surrounding rock deformation and the presence of impact ground pressure, which puts forward higher requirements for coal mine support technology. In order to ensure the safety and efficiency of coal mining, the support technology needs to be optimized and upgraded. At present, coal mine support technology has made great progress, including reinforced concrete support, anchor support, grouting support, slab support and so on. These technologies have played an important role in coal mining, but there are still some problems in deep roadway support. (Jucai Chang et al., 2009; Hongpu Kang et al., 2015).

In the anchorage design code currently in use(National Standard Writing Group of the People's Republic of China,2015), when the anchor cable is used for the anchorage of a jointed rock body, the lateral shear effect of the anchor cable must be considered in addition to the axial tensile effect of the anchor cable. The lateral shear effect of the anchor cable is mainly manifested in the lateral restraint effect of the anchor cable on the structural face. When the jointed rock body slides or has a tendency to slide along the structural face, the lateral restraint of the anchor cable can resist the lateral shear of the structural face, thus preventing the rock body from sliding or separating along the structural face. However, when the lateral shear force at the structural face exceeds the load-bearing capacity of the anchor cable, the anchor cable may be sheared off at the structural face, resulting in anchorage failure. Therefore, when designing the anchorage structure, it is necessary to consider the axial tensile strength and lateral shear strength of the anchor cable, and to determine the parameters such as material, diameter, length and anchorage method of the anchor cable in combination with the specific engineering conditions and structural requirements to ensure the stability and reliability of the anchorage structure.

Engineering practice and previous studies have shown that anchor rod anchorage failure as well as anchor cable anchorage damage are caused by the combined action of the axial force and transverse shear force of the anchor solid(Xiurun Ge et al., 1988). The damage of anchorage structure is caused by the combined action of several factors, including the axial force of anchor cable, transverse shear force, and deformation of surrounding surrounding rock. Particularly, for nodular rock anchorage, the lateral restraint of the anchor cable on the structural face is very strong due to the sliding and sliding tendency on the structural face, which can lead to the generation of lateral shear forces and thus affect the force state of the anchor cable. Therefore, the axial force and lateral shear action of the anchor cable must be taken into account when assessing the stability and tensile and shear resistance of the anchored structure. The existing research needs to be further explored and improved to establish a more complete anchorage theoretical system and failure criterion to improve the reliability and safety of engineering practice.

The development of anchoring technology has indeed brought great economic and social benefits, but at the same time there are also some challenges and difficulties. As the core component of anchorage system, the evaluation and optimal design of anchor performance are very important to ensure the engineering safety. Although there are many mathematical models and theoretical calculation methods for anchor rods, there are many types of anchor rods and complex field environment, and it is difficult to match completely between the theoretical calculation results and actual engineering measurement results, so there is still some blindness in the evaluation and optimal design of anchor rod performance in actual engineering. In order to solve these problems, a combination of various means, such as field tests, numerical simulations, and empirical formulas, is needed to make a comprehensive evaluation and optimal design of anchor rod performance. Also, for different types of anchors, corresponding evaluation and design criteria need to be developed for their characteristics and application scenarios in order to ensure the safety and reliability of the project.(Haomin Guo. 2021).

1.2 Current study

1.2.1 Current study of anchor cable support for coal mine roadway

Due to the poor geological conditions of the coal mine tunnel, the surrounding rock is broken and easy to collapse, in order to ensure the safety of miners and the smooth production of coal mine, support measures must be used. The basic principle is to use anchor rods and anchors embedded in the wall rock of the roadway to form a certain support system, so that the surrounding rock and anchor rods have a synergistic effect, bearing the pressure of the rock around the roadway to achieve the purpose of stabilizing the surrounding rock, controlling deformation and preventing collapse. At present, the anchor cable support technology of coal mine roadway has been widely used and new development has been made. With the progress of science and technology, the material and technology of anchor rods have been improved, and the construction of anchor cables has been gradually improved to meet the higher requirements of support.

Anchor rods and anchor cables are the main support materials for coal mine roadway rock control. Anchor cable has significant features compared to anchor rod. Anchor cable has higher support strength and load bearing capacity. Because anchor cable can be applied with large preload, it can obtain more ideal support effect, and its reinforcement range, support strength and reliability are better than ordinary anchor rods. The anchor cable can be bent to adapt to the more complex geological conditions of the roadway. The length of anchor cable can be more than 10m, which can anchor the shallow unstable surrounding rock with the deep stable surrounding rock in the limited roadway space, so as to achieve better surrounding rock control effect. The construction of anchor cable is convenient and the cost is low. Anchor cable is easy to fabricate and install, so it can be completed quickly, and the cost of anchor cable is lower than that of anchor rod, which is more economical for large-scale support projects. Anchor cable is highly adjustable. Since anchor cable has large preload, the tension of anchor cable can be adjusted at any time after anchoring to adapt to the deformation and changes of the roadway surrounding rock and maintain the stability of the surrounding rock. In short, anchor cable as a new type of roadway support material has more outstanding advantages than anchor rod, and has been widely used in coal mines, tunnels, underground engineering and other fields.

Since anchor cables were applied to the rock reinforcement of mining projects in the 1960s, they have made great development and progress, and various types of anchor cables have been formed to adapt to different types of surrounding rocks. The introduction of anchor cable in coal mine roadway support has given a significant impetus to the development of roadway support and improved the reliability of roadway support. The application range of anchor support has been expanded. Foreign coal seam mining conditions are relatively simple, anchor cable is mostly for reinforcement support, while domestic coal seam mining conditions are relatively poor, with the increase of mining depth in China, the use of anchor cable has increased significantly, even some roadway support means using all anchor cable support, anchor cable plays an increasing role in China's coal mine roadway surrounding rock control. (Chen et al., 2018)studied the mechanical transfer mechanism of full-length grouted anchor cable in soft rock and concluded that changing the structure of anchor cable in soft rock can significantly improve its reinforcement effect.(Yonglian Li et al., 2017) studied the overall characteristics of the actual stresses on anchor cables in the roof of deeply deformed roadways, and concluded that the roof anchor cables were subjected to not only axial tensile loads but also lateral shear loads when breaking, and the closer to the middle of the roof the greater the tensile loads were, and the closer to the roadway gang the more significant the shear loads were. And the multi-layer support technology of long anchor cable and short anchor cable and anchor rod was proposed. (Manchao He et al., 2014) proposed the constant resistance large deformation anchor cable support technology according to the deformation characteristics of impact ground pressure roadway.(Hongpu Kang et al., 2007)proposed an innovative support technology with high-strength anchor rods and high preload in order to cope with the problem of large deformation of the surrounding rock in the deep roadway and to ensure the stability of the working face roadway support.

1.2.2 Current study on anchor cable shear mechanics test method

The shear force of the anchor cable refers to the shear strength generated by the anchor cable when restraining the rock mass(Shuangsuo Yang et al., 2003). Anchor cables as a form of restraint are mainly used in roadway rock support to stop excessive deformation of the surrounding rock generated by the relative misalignment along the structural face. In this process, the anchor cable generates shear stresses as it restrains the rock on either side of the joint face, counteracts the shear forces along the joint face, and generates normal stresses on the surface of the cable body. These forces improve the overall strength and stability of the rock mass and prevent the rock mass from sliding or breaking at the weak face.

The anchor rods are fixed in the surrounding rock by anchoring action, which makes the anchor rods and the surrounding rock form a whole, thus jointly bearing the ground pressure and load, reducing the influence of underground buildings on the surrounding rock and improving the bearing capacity of the surrounding rock. Reducing the self-weight of the structure: While anchor rods are fixed in the surrounding rock, they can bear part of the self-weight of the structure and reduce the load of the underground buildings on the surrounding rock, thus reducing the influence of the self-weight of the structure on the surrounding rock and helping to improve the stability of the surrounding rock. Saving engineering materials: Anchorage support technology can save engineering materials by improving the stability of the surrounding rock and reducing the quantity and amount of other support materials used. Safety and efficiency: Anchorage support technology can improve the stability of the surrounding rock and reduce the influence of underground buildings on the surrounding rock, thus reducing the risk of underground engineering and improving the safety and efficiency of engineering construction. Significant economic and social benefits: anchorage support technology can improve the safety and efficiency of underground engineering, reduce the use of support materials and lower the project cost, and also help to improve the utilization rate of underground space, which is of great significance to the development and construction of cities.(Pual et al., 2015)

The anchor cable (rod) shear test is a common test method for assessing the performance of anchor systems. There are two main methods of anchor shear testing, one is a double shear test method and the other is a single shear test method. The main difference between them is the number of shear surfaces in the specimen. The double shear surface test method involves drilling two parallel holes in the concrete specimen and inserting the anchor rod into each of the two holes to form a double shear surface test model. In the test, the shear performance of the anchor rod in concrete is investigated by applying a horizontal shear force to break the concrete specimen. This test method is commonly used to investigate the static load performance and anchorage capacity of anchor rods. The single shear surface test method involves drilling a hole in the concrete specimen and inserting the anchor rod into it to form a single shear surface test model. In the test, the concrete specimen is broken by applying horizontal and vertical shear forces to investigate the shear and pull-out properties of the anchor rod in concrete. This test method is commonly used to investigate the fatigue performance and anchorage capacity of anchor rods. The test protocol design needs to be fully validated and experimentally verified to ensure that the test results.

Dulacka's instrument was designed in 1972 and was able to measure the shear mechanical properties of the smallest diameter anchor rods known at the time. However, it had limitations in measuring larger diameter anchors and had a limited range of shear displacements. Since 1972 there have been significant technical advances and improvements in the test equipment used to measure the mechanical properties of anchor rods. Newly designed instruments can handle larger diameter anchors and provide a greater range of shear displacement measurements. (Dulacka., 1972)

Bjurstrom designed the Anchor Rod Shear Test Apparatus in 1974, which is an experimental apparatus for studying the performance of anchor rod members under shear forces. This apparatus allows smooth adjustment of the axial force on the anchor member and can be adjusted for different anchorage angles to simulate the forces on the anchor member in practical engineering applications. (Bjurstrom., 1974)

The anchor single shear apparatus designed by Dight in 1983 was mainly used to determine parameters such as the shear strength of rocks in rock mechanics experiments. However, the relatively small displacement range during shear may limit the use of this apparatus in some experimental conditions. Specifically, if a large displacement deformation of a rock sample is required in a shear test, then the instrument may not be able to meet the requirements. (Dight et al.,1983)

The single-shear apparatus is a common mechanical test apparatus for testing the shear properties of materials. Spang K designed the single-shear apparatus to test the shear resistance of cement mortars, including the ability to determine the force along the normal direction, shear force and other parameters of the cement mortar during the test. (Spang K et al., 1990)

One of the advantages of Pellet F's independently designed single shear test for anchor rods is that the anchor rod installation angle can be adjusted to suit the test content. This design allows the test to be more flexible and controllable to suit different test requirements and surrounding rock characteristics. In addition, the test allows for three-dimensional loading of the surrounding rock mass, which makes the test results more realistic and reliable, and better simulates actual rock engineering scenarios, and allows for three-dimensional loading of the surrounding rock mass during the test. (Pellet F., 1994)

In 1995 Ferrero proposed a new single-shear test method that significantly reduces the frictional forces on the rock joints during shearing, reducing the impact on the test results as there is no contact between the rock joints. (Ferrero., 1995)

The single-shear device designed by Bawden is an experimental device for testing the effect of joint position on anchor cable stiffness and bearing capacity, which can simulate anchor cable stiffness and bearing capacity under different conditions by adjusting the position of the joint position in the specimen. (Bawden et al.,1994)

The single shear test method proposed by Ron in 2015 is a test method that can be closer to the actual engineering situation, and is designed to test the single shear strength and displacement response of the anchor to the rock mass. The test method features the anchor rod and rock mass as two separate shear bodies, and multiple combinations of loading methods can be performed during the test to simulate different engineering conditions and practical situations. However, the large size of the test may increase the difficulty and complexity of the test and special measures are required to ensure the accuracy and reliability of the test. In addition, adequate test design and calculations need to be carried out before conducting the tests to ensure that the test parameters and conditions are reasonable and feasible. (Ron et al.,1994)

The University of New South Wales used numerical simulation software to investigate the effect of different parameters on the mechanical properties of anchors in shear by simulating the variation of these parameters, such as material properties, geometry and stress conditions, etc. (Hagan,P. et al., 2014)

The University of Wollongong designed a double shear test rig, which has the advantage of being able to apply different preload forces during the test and the external prefabricated high stiffness steel frame prevents the concrete from crumbling and the anchor cable from popping out during the test, greatly improving the safety of the test scientifically valid and reproducible. (Aziz,N. et al., 2003)

1.2.3 Current study of shear mechanical behaviour of anchor cables in jointed rock masses

The interaction between the surrounding rock and the anchor rods is complex, and there are many factors affecting the anchoring effect of the anchor rods on the jointed rock, such as the strength of the rock around the anchor rods, the preload applied before the test, the installation angle of the anchor rods, the roughness of the surrounding rock joint surface, the angle of internal friction, the type of anchor rods such as different anchor rods, etc. For these factors, scholars and experts at home and abroad have conducted various studies. The main research results are as follows:

Rock strength is one of the most important factors influencing the mechanical behaviour of shear deformation in jointed rock masses. In higher strength rock masses, the shear and tensile strengths of the surrounding rock are relatively high, so the stresses on the surrounding rock on both sides of the joint face are relatively smooth, the stresses are relatively evenly distributed and the stability of the anchor cable is relatively good. In the lower strength rock, the shear and tensile strengths of the surrounding rock are both lower, so the stresses on the surrounding rock on both sides of the joint face are more complex, and stress concentration and damage can easily occur, resulting in the stability of the anchor cable body being affected. In addition, the development of joint faces may be higher in lower strength rock masses, and factors such as the spacing of the joint faces and the dip angle of the joint faces may also have an impact on the stress distribution and development of the anchor cable. In addition, the strength of the rock mass also affects the form and extent of the distribution of the plastic zone in the surrounding rock near the joint face, which directly determines the deformation characteristics and failure mode of the anchor cable. In engineering practice, the determination of the surrounding rock strength parameters is an important basis for rock mechanics analysis and anchor cable design. By determining and analysing the strength parameters of the surrounding rock, it is possible to provide the necessary basis for the selection, deployment and calculation of the anchorage force of anchor cables. Spang and Egger (Spang K. et al., 1990) showed that anchoring can effectively enhance the shear deformation resistance of rock masses in anchored rock masses. In addition to this, Ferrero (Ferrero., 1995) found that the mode of fracture failure of anchor rods under misalignment of the surrounding rock was caused by the combined action of lateral axial forces. This mode of failure usually occurs when the overall strength and stiffness of the rock mass is high, when the rock mass and anchor rods are subjected to high stresses and the anchor rods are unable to withstand the stresses and fracture, and then fail when the rods reach their strength limit and break in tension. This failure mode usually occurs when the overall strength and stiffness of the rock mass is low, when the rock mass and anchor rod are under less stress and the anchor rod develops a higher strain at the plastic articulation point, eventually breaking under tension.Aziz (Aziz,N. et al., 2003) carried out a double shear test with a self-designed test rig and found that the shear strength of the anchor cable at 40Mpa surrounding rock was greater than that at Schubert (Schubert.P, 1995) conducted a double shear test with full-length grouted anchors to investigate the anchoring effect of full-length grouted anchors at different rock strengths, and the results showed that the overall shear displacement of the system was substantially reduced in hard rock compared to soft rock. (Teymen. et al., 2003) used numerical simulation software, based on the indoor double shear tests conducted by previous authors, to analyse the Pre-tensioned anchors were better anchored than ordinary anchors, and it was found that the higher the rock strength, the better the anchors could perform shear resistance and the better their anchoring effect. Zhang Wei et al (Wei Zhang. et al., 2014)conducted an indoor test to investigate the anchoring mechanism of anchor ropes for anchoring nodal rock under the condition of relative sliding of the structural surface of the rock mass, and the test results proved that the anchor ropes could play a better anchoring effect under the condition of higher surrounding rock strength. Liu Aiqing et al (Aiqing Liu. et al., 2013) used FLAC3D software to study the shear strength of anchor rods with the same preload for different surrounding rock strengths. They also found that the shear force of anchor rods in hard rock was 70kN greater than that in soft rock when the preload was the same.

Preload is also an important factor in the anchoring effectiveness of anchoring materials. Preload is a certain amount of tensile force applied to the anchor rod prior to anchoring, which can improve the bond between the anchor rod and the surrounding rock and improve the distribution of forces on the rod, thus increasing the tensile performance and service life of the anchoring material. In general, to ensure the stability and reliability of the anchor material, the preload force needs to be set reasonably according to the nature of the surrounding rock and the engineering requirements. The size of the preload force needs to be adjusted according to the specific situation. In general, the size of the preload force should be controlled between 60% and 80% of the tensile strength of the anchor to ensure the stability and reliability of the anchor material. Liu Aiqing et al conducted anchor rod direct shear tests in the laboratory, setting different preloads to study the shear resistance of the anchored rods under different preloads. The results showed that increasing the preload could increase the initial shear strength of the nodular rock mass. Haas (Haas. et al., 1981) carried out an indoor test based on the shear performance of resin anchors. Ferrero found that increasing the preload had an effect on the shear deformation in the early stages of the shear process, as shown by the fact that the slope of the shear-displacement curve at the initial stage was greater than the slope of the shear stiffness at the later stages of the shear test. The slope of the shear-displacement curve at the initial stage was greater than that at the later stage. Li Yongliang found in an indoor double shear test of concrete anchor ropes that increasing the preload could improve the initial shear stiffness of the anchor ropes anchoring the nodal rock mass.

The roughness of the nodal shear surface is also an important factor affecting the shear stiffness of the rock mass anchored by the anchor rod. The roughness of the nodal shear surface affects the friction and bond between the anchor and the surrounding rock, thus affecting the shear stiffness of the rock anchored by the anchor. Specifically, when the roughness of the joint shear surface is small, the bond and friction between the anchor rod and the surrounding rock is small, and the shear stiffness of the anchor rod is correspondingly small. Spang and Egger carried out an indoor shear test with different roughness of the joint surface, and the shear stiffness of the anchor rods increased by 50% in the rough joint surface compared to the smooth joint surface as the friction coefficient of the joint surface increased. Goris and Martin et al (Goris J M. et al., 1996) carried out a series of tests setting up concrete of different strengths for shear tests, and the shear strength of concrete with rougher nodal surfaces was much greater than that of smoother nodal surfaces. stillborg, Aziz and Yang Renshu et al through shear tests of anchor ropes can conclude that to make shear breakage of the anchor cable to occur, a certain shear displacement needs to be achieved. (Stillborg B. et al., 1996)This is because, when the anchor cable is subjected to lateral forces, the anchor cable is subjected to a certain shear force, and when the shear force exceeds the strength limit of the anchor cable, the anchor cable will break in shear. (Renshu Yang. et al., 2014). Dolinar observed in the field that the relative sliding of the rock on both sides of the joint face caused the anchor cable to have a shear displacement of at least 50-100 mm before the anchor cable would fail. (Dolinar D R. et al., 1996) Zabuski chose anchors with diameters ranging from 5 mm to 25 mm and shear expansion effects occurred when shear tests were carried out on the jointed surfaces of concrete specimens. (Zabuski. et al., 1991). This effect is where the rough shape of the jointed surface causes the concrete to expand outwards when the specimen is subjected to shear, thus producing an axial force on the anchor rod and increasing the shear strength of the anchor rod. This effect is caused by the properties of the concrete material and the geometry of the specimen. When shear tests are carried out on the jointed surface of the specimen, the friction of the concrete on the jointed surface increases, which causes the concrete around the jointed surface to expand outwards, forming a cone-like area of expansion. Liu, Quansheng et al analysed the shear tests on jointed rock masses and found that two modes of yielding damage were produced during the shear of the joint surface, and the concept of "equivalent shear area" was proposed. (Quansheng Liu. et al., 2018)The concept of "equivalent shear area" was introduced in the study. This parameter can be used to calculate the shear strength of the jointed rock more accurately. Wen Jintao et al conducted a shear test on the anchor cable anchoring the jointed rock mass, focusing on the effect of the roughness of the jointed structure surface on the anchoring effect of the anchor cable, the effect of the change in anchor cable anchoring angle on the smooth structure surface did not exceed 15%, and the effect on the rough structure surface was about 30%.(Jintao Wen. et al., 2003). Wang, Chinese et al used numerical simulation software to simulate the roughness and surface shape of different surrounding rock contact surfaces. The shear strength of anchor rods tends to increase and then decrease as the anchorage angle increases. (Zhongwen Wang. et al., 2010)

The anchorage angle is an important factor in the interaction between the anchor rod and the anchorant and the surrounding rock. The anchorage angle is the angle between the contact surface of the anchor rod and the surrounding rock, which is an important factor affecting the shear strength and shear displacement of the anchor rod. When the anchorage angle is small, the friction between the anchor rod and the surrounding rock is small and the anchor rod is susceptible to shear damage due to lateral forces, while when the anchorage angle is large, the anchor rod is susceptible to sliding, which also affects the shear strength and shear displacement of the anchor rod. Therefore, a suitable anchorage angle needs to be selected according to the specific engineering conditions and anchor requirements in order to ensure the stability and safety of the anchor rod. Different anchorage angles will result in different force distribution and bond size, thus affecting the tensile performance and service life of the anchor rods. Therefore, in practical engineering, suitable anchorage angles need to be selected according to different surrounding rocks and construction conditions to ensure good bonding and even force distribution between anchor rods and surrounding rocks, as well as to ensure a smooth construction process. For specific engineering problems, the optimum anchorage angle needs to be determined by means of tests and simulation calculations to ensure the quality and safety of the project. At home and abroad, there has been a lot of research on anchorage angles and a wealth of experience and technology has been accumulated. The relevant research results have been widely used and good results have been achieved. Haas found that the shear stiffness of anchor ropes installed vertically was less than the installation angle of anchor ropes installed at an inclination, (Hass et al., 1981)and Azuar (.Azuar J J, 1977) carried out indoor tests and concluded that the shear force of anchor ropes installed vertically could only reach Egger and Fernandes (Egger et al., 1983) carried out several sets of indoor tests by varying the angle at which the anchor ropes were installed. Homlberge found that the deformation of the anchor rods was four times greater when they were installed vertically than when they were installed at an angle of 60°. .(Holmberg M, 1991) Yoshinaka carried out straight shear tests using anchor rods with no preload applied, and when the anchor rods were installed at an angle in the range of 30° to 60°, the The best anchoring effect was achieved when the anchor was installed at an angle of 30° to 60°. (Yoshinaka R. et al., 1987) Egger and Fernandes showed that the shear displacement of the anchor rods was minimised when the anchor rods were installed at an angle between 40° and 50° in an indoor test of anchor angle. (Egger et al., 1983) Maiolino found that at an anchorage angle of 90°, the angle of contact between the anchor and the surrounding rock was greater and the friction was lower, so that the anchor was prone to sliding, resulting in a reduction in shear strength. In contrast, when the anchorage angle was 45° or 60°, the angle between the anchor rod and the contact surface of the surrounding rock was smaller, the friction force was higher and the shear strength of the anchor rod was higher. (Maiolino S. et al., 2015). Hibino and Motojima demonstrated that the anchorage angle does not affect the anchorage effect of the anchor cable. (Hibino S. et al., 2015).

1.2.4 The main problems

In summary, a great deal of research work has been carried out by domestic and international scholars on the axial mechanical properties of anchor cables, which has solved a large number of roadway support problems. However, with the increase in mining depth and intensity, the use of full-length grouted anchor cables and grouted anchor cables has increased significantly with the increase in large deformation of the roadway. If the true deformation characteristics of full-length grouted anchor cables and the reinforcement mechanism of jointed rock are not understood, it is difficult to propose economical and effective support countermeasures for coal mine roadway rock stability control. At present, the study of the shear mechanical behaviour of full-length grouted anchor cables faces a number of problems and challenges.

(1) Research on the shear mechanical behaviour of full-length grouted anchor ropes is weak due to insufficient consideration of the shear slip of the jointed rock mass, and the mechanical nature of the stage deformation and even fracture of full-length grouted anchor ropes is not well understood.

(2) The research on the reinforcement mechanism of full-length grouted anchor ropes is mostly in the axial direction, but the shear resistance of the anchor ropes during the shear slip of the joint is not yet studied in depth, and the mechanism of full-length grouted anchor ropes reinforcing the jointed rock mass is not sufficiently understood.

1.3 Research content and flow chart of the study

1.3.1 Research content

(1) Study on the shear mechanical characteristics of full-length grouted anchor ropes under the influence of different factors

Four types of anchor ropes (including common anchor ropes and grouted anchor ropes) commonly used in coal mines were selected, and the self-developed anchor rope shear test system was used to study the influence of preload, rock strength and rope type on the shear mechanical behaviour of full-length grouted anchor ropes, and to obtain the characteristics of the influence of corresponding factors on the peak shear strength and shear displacement of full-length grouted anchor ropes, as well as the shear stiffness of the jointed rock mass.

(2) Anchorage mechanism of full-length grouted anchor ropes to jointed rock masses

The study constructs a mechanical model of the interaction between the full-length grouted anchor cable and the jointed rock mass, further investigates the force-deformation characteristics of the anchor cable under the influence of the preload force, the roughness of the structural surface, the strength of the rock mass and other factors, integrates the control effect of the coupling effect of the axial tension and lateral shear of the anchor cable in the jointed rock mass on the shear slip of the jointed rock mass, obtains the mechanism and mode of action of the full-length grouted anchor cable on the shear performance of the jointed rock mass, and reveals The mechanism and mode of action of full-length grouting anchor cables on the shear properties of jointed rock masses are obtained to reveal the intrinsic mechanical mechanism of full-length grouting anchor cables on jointed rock masses.

1.3.2 Research methodology and flow chart

(1) A set of anchor cable double shear test system was designed for the purpose of conducting shear tests on full-length grouted anchor cables. The anchor cable double shear test system was used to investigate the influence of rock strength, preload force, cable type and other factors on the force and deformation characteristics of full-length grouted anchor cables during shear, including the cable force-displacement curve, peak shear strength and nodal shear stiffness.

(2) Numerical simulation analysis of the full-length grouted anchor cable shear test can be derived to derive the overall force characteristics of the anchor cable body. Through the bonding effect of the anchoring agent, the anchor cable and the surrounding rock form a unified bearing system, which greatly increases the overall shear strength of the system. The results of the numerical simulation show the force characteristics of the anchor cable and the surrounding rock mass, and reveal the interaction between the jointed rock mass and the full-length grouted anchor cable.

(3) Combining the above research results, the mechanical analysis is carried out by applying the relevant previous theories to fully consider the control effect of the coupling effect of axial tension and lateral shear of the full-length grouting anchor cable in the jointed rock mass on the shear slip of the jointed rock mass, to clarify the mechanism and mode of action of the full-length grouting anchor cable on the shear performance of the jointed rock mass, and to reveal the inner mechanical mechanism of the full-length grouting anchor cable on the anchorage of the jointed rock mass.

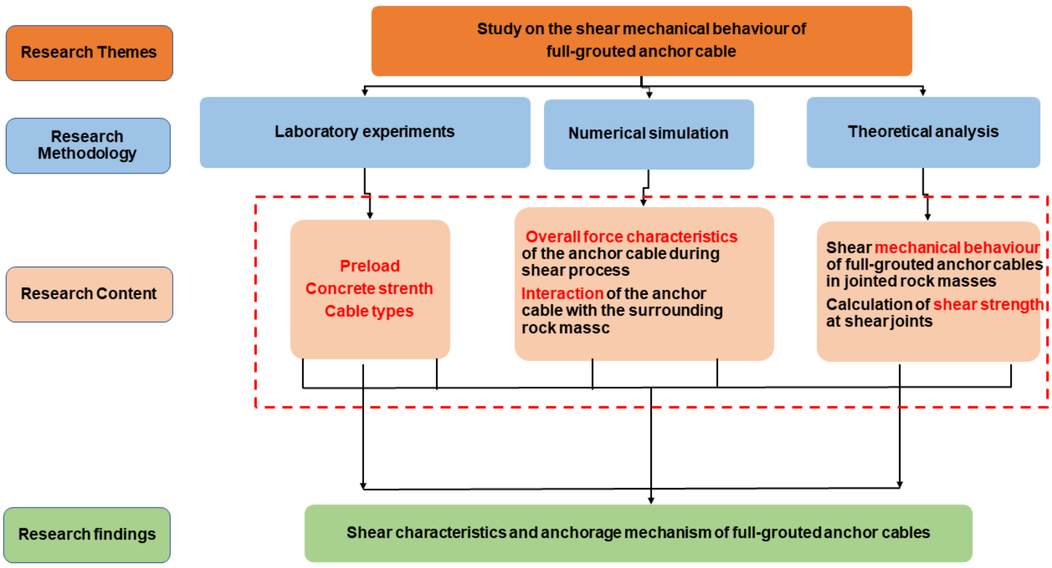


Figure 1 Research flow chart

2 Anchor cable shear systems and test programmes

It can be seen from the summary of previous research results that previous studies have often focused on the reinforcement effect of anchor rods on the structural surface of rock joints and the mechanical properties and anchorage effect of anchor cables in tension. Less research has been carried out on the shear mechanical properties of anchor ropes. In coal mine roadway support sites, misalignment of structural faces between the surrounding rock may lead to shear damage, which is a common form of damage. Structural faces in the surrounding rock are faces within the rock formation with different lithological, tectonic and deformation characteristics. They are usually naturally occurring or may be artificial structural faces due to engineering activities.

The presence of structural faces can have a significant impact on the strength and stability of the surrounding rock. When an anchor cable is subjected to shear, the misalignment of the structural face can cause strong local damage to the surrounding rock, leading to anchor cable failure. Therefore, in practical engineering, the presence and characteristics of structural faces need to be thoroughly investigated and analysed to ensure that the anchor cables are designed and arranged to effectively resist the effects of shear damage and to safeguard the safety and stability of the project. The understanding of the mechanical behaviour of anchor cables under the joint action of tension and shear is the basis for revealing the anchorage mechanism of full-length grouted anchor cables. At the same time, the research on anchor ropes is limited to the overall anchoring effect on the surrounding rock, but there is less research on the deformation and damage extension of the hole and rock mass during shear, the law of tensile shear damage, and the interaction between grouting anchorant and anchor ropes and rock mass.

In this chapter, a double shear test system for anchor ropes was designed in order to conduct a shear test of full-length grouted anchor ropes based on the existing research status and on the basis of existing work. Common mining anchor cables were selected to consider the anchor cable shear test under different factors. These factors are: preload, concrete strength and type of cable body. The effects of these factors on the shear force and deformation characteristics of the full-length grouted anchor ropes, including the axial force, shear-displacement curve, peak shear strength and nodal shear stiffness of the ropes, were obtained.

2.1 Anchor cable shear test systems

2.1.1 Experimental model design

There is no fixed international standard for anchor cable shear testing. Based on previous tests, anchor cable shear tests can be broadly divided into two categories, one being single shear and the other being double shear. Single shear tests, where only one shear surface exists, are difficult to carry out indoors due to the restrictive test conditions. The double shear test system used in this paper has two shear surfaces and is symmetrically arranged, making it easy to keep the device stable. It is convenient for the fixation of the specimen and the overall smooth conduct of the shear test. This ensures that the final test data is true and reliable.

The test does not take into account the installation angle of the anchor cable. The anchor cable is installed in the direction normal to the knuckle face and is tested in straight shear with the knuckle face, meaning that the anchor cable is installed in the same direction normal to the knuckle face and the shear force applied in the test is also in the direction of the knuckle face. This test method is used to assess the shear strength and anchorage capacity of the anchor cable under the direct action of the joint face, as well as the interaction between the surrounding rock and the anchor cable. This test method can better simulate the interaction between the anchor cable and the nodal face in actual engineering, which helps to assess the effectiveness of the anchor cable and the stability of the surrounding rock. At the same time, by comparing and analysing the test results under different rock strengths, it can provide a reference basis for the design and arrangement of anchor cables in actual project.

The anchor cable shear test system was designed in-house and consisted of three concrete test blocks of a certain strength, side by side, the concrete in the middle measuring 300mm x 300mm x 450mm and the concrete on either side measuring 300mm x 300mm x 300mm. The overall concrete test block length was 1050mm and the concrete was in contact with each other. The centre was drilled through a special mould for casting the concrete test blocks and then pre-drilled with 28mm anchor cables in stainless steel steel tubes. Grouting holes of 16mm diameter are drilled on the top of the concrete test blocks on both sides by means of an electric drill.

Pressure transducers with a range of 500kN are arranged on both sides of the specimen to record the value of the preload force during tensioning of the anchor cable and the change in the axial force of the anchor cable during the shear test. The pallets are arranged in front and behind the pressure transducers and finally fixed with anchors to ensure that the anchor cable does not pop out during the test and to ensure the safety of the test. The test blocks at both ends are cushioned by 120mm so that the middle is overhung to ensure sufficient shear displacement during the shear test. The press provides the shear force by loading the concrete specimen in the middle. Three concrete test blocks are required for each set of shear tests.

2.1.2 Introduction to the test system

(1) Test loading system

The test loading system is based on the ZHYD-2000 split hydraulic jack. The maximum range of the jack is 2000kN and the maximum stroke available is 200mm, with a channel for connection to a measurement system to record the change in pressure throughout the test. The loading is fully manually controlled, using the static pressure provided by the hydraulic oil output from the two hoses of the loading system to apply a constant pressure to the system. The whole machine has high strength and good stability. The shear rate is kept constant during loading at 1mm/min.

Figure 2 Test loading system

As the stiffness of the chosen anchor cable is much greater than that of the concrete test block, in order to avoid the concrete test block breaking while the anchor cable has not yet reached yield, the concrete test block needs to be assembled into a prefabricated steel mould before the test starts, with a special high strength cover added to the top and screwed all around to make the overall stiffness of the test system meet the shear test requirements and to ensure that the anchor cable can be sheared smoothly. The bottom part is made of a piece of H-beam as the base and provides the counter force for the hydraulic jack. The concrete test blocks on both sides are raised by 120mm with pads, leaving the middle block suspended to ensure sufficient shear displacement is provided during the test.

(a) Before loading

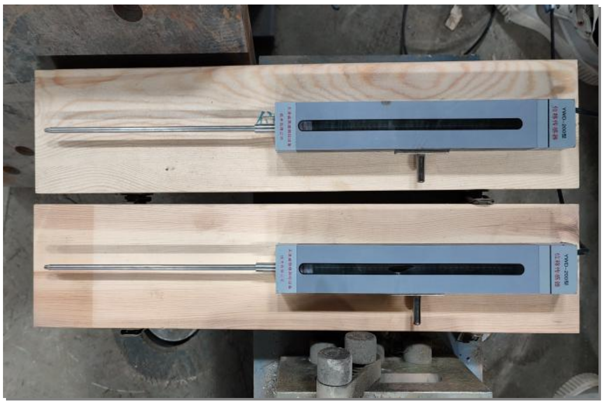
(b) Loading **(c) After Loading**

Figure 3 Diagram of the test loading process

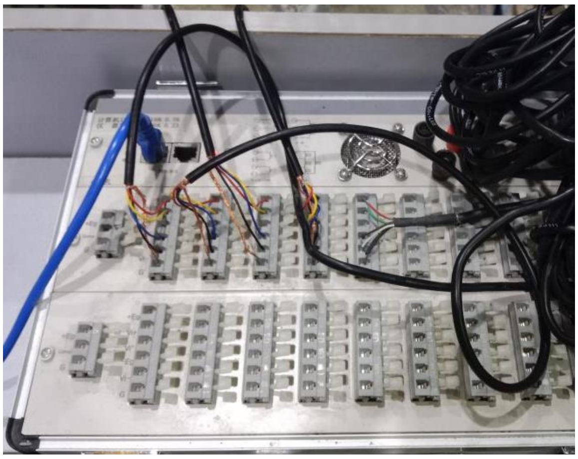
(2) Data acquisition system

The data acquisition system used for the test is shown in Figure 2.4. The data acquisition box used for the test can be divided into a total of five channels. The range of the displacement gauge used for the test was 100 mm. The anchor gauges used to measure the change in axial force during shear at both ends of the system have the relevant parameters as shown in Table 2.1. After adjusting their accuracy, they were connected to the data acquisition box. The loading device during the shear test is a hydraulic jack with a range of up to 2000 kN and a maximum stroke of 200 mm available. the change in shear force during the test is monitored and recorded. The data from the data acquisition box is fed into a computerised data acquisition system to monitor the changes in shear displacement, anchor cable axial force and shear force during the test in real time. After the test rig has been assembled, it needs to be manually calibrated and zeroed on the software side of the computerised acquisition system before the test is started and data collected.

（a） Piercing pressure sensors



（b）Displacement meter



（c） Data collection box

（d）Data Acquisition Centre

Figure 4 Test measurement acquisition systems

2.2 Test material

2.2.1 Preparation of anchor cables

The anchor ropes used in this test are all standard anchor ropes commonly used for roadway support in mines. According to the number of anchor strands, they can be divided into 1×7 and 1×19 structural anchor cables, of which 1×7 structural anchor cables can be divided into 17.8mm and 21.6mm in diameter. The 1×19 structural anchor cable is of 21.8mm diameter. In total, four types of ropes were used.

Figure 5 Type of cable bolt used in the test

2.2.2 Concrete test block preparation and strength testing

(1) Concrete placement and maintenance

Each set of concrete was cast with three test blocks, corresponding to the two sides of the shear test system and the middle test block. The mould size used for casting is 450mm x 300mm x 300mm in the middle and 300mm x 300mm on both sides, with a 28mm hole reserved for the anchor cable in the middle, and three standard small test blocks for each group for subsequent uniaxial compressive strength testing. The standard mould size for the small test blocks is 150mm x 150mm x 150mm.

Figure 6 Concrete casting moulds

1) Mould cleaning

Cleaning is a very necessary step before the concrete is placed to ensure the accuracy and reliability of the test results. During the cleaning process, foreign objects such as soil and debris need to be removed from the moulds to avoid any impact on the test results. It is also necessary to ensure that the surface of the mould is smooth to allow for the flow and filling of the concrete. In addition to cleaning the inside of the mould, a uniform layer of release agent needs to be charted on the internal surface of the mould to allow for smooth release once the concrete has set. Commonly used release agents are dimethyl silicone oil, liquid wax etc. The release agent used in this test is dimethyl silicone oil release agent. Dimethyl silicone oil release agent has the advantages of being easy to work with and not affecting the properties of the concrete, so it is more common in practice. It is important to note that the release agent should be applied uniformly and with full coverage to avoid forming adhesion on the concrete surface. At the same time, it is also necessary to select the appropriate type of release agent and construction method according to the specific concrete mix and test requirements.

2) Concrete preparation

Mixing is an important part of the concrete specimen preparation process and can directly affect the mechanical properties and quality of the specimens. Before mixing concrete specimens, various materials need to be accurately weighed and put into the mixer for mixing in accordance with the test requirements and concrete mix ratio. In the mixing process, various materials such as stone, cement and sand should be poured into the mixer in turn and dry mixed to ensure that the various materials can be fully mixed. Then gradually add the appropriate amount of water for wet mixing, while continuing to mix for about 10 minutes until the concrete is uniform. It should be noted that the water to ash ratio should be strictly controlled during the mixing process so that the concrete is not too thin or too dry, which will affect the strength and quality of the specimens. Attention also needs to be paid to the choice and use of mixers to ensure that the concrete is well mixed, free of air pockets and lumps, thus ensuring the mechanical properties and quality of the specimens.

Figure 7 Concrete mixers

3) Pouring of the test blocks

The well-mixed concrete in the mixer was added to the prefabricated moulds with sufficient mixing time to ensure the homogeneity and compactness of the concrete. As the concrete moulds were too large to be placed on the vibrating table, they were fully vibrated with a vibrating bar for 10 minutes to exclude as many air bubbles as possible from the concrete and to ensure the quality of the test blocks. After pouring the concrete, the test blocks were left to stand for more than 12 hours, waiting for the concrete to set completely before proceeding to the subsequent experimental steps. After confirming that the concrete has set completely, pull out the pre-placed steel pipe.

Figure 8 The process of vibrating concrete

4) Conservation

After demoulding, the specimens need to be placed in a cool, damp place for curing, avoiding exposure to the sun or excessive dryness. Regular watering is required to keep the surface of the specimen moist and to promote the early strength development of the concrete. For small specimens, the specimens should be maintained in a special curing room. The temperature and humidity in the curing room needs to be controlled within the appropriate range, typically 20±3°C and 97% to 99% humidity. This will improve the strength and durability of the concrete and ensure the accuracy of the test results. Care must be taken to prevent damage to the surface of the test blocks during curing, which may affect the test results.

Figure 9 Concrete test block maintenance

(2) Strength testing of concrete standard small test blocks

In order to check whether the strength of concrete meets the test requirements, uniaxial compressive tests are also carried out on the finished concrete small test blocks before the formal shear test. Uniaxial compressive strength is generally used as the basic strength indicator of concrete in building design and testing. In order to measure the uniaxial compressive strength of the test blocks, standard cubic specimens cast for indoor testing were selected and cured for 28 days under standard.

The loading system used for the test is the Changchun YAD-2000 electro-hydraulic servo press.conditions before being tested for uniaxial compressive strength. YAD-2000 type single screw. The YAD-2000 single screw press is suitable for compressive testing of multiple specimens of different sizes. It is possible to perform program-controlled tests under the standard requirements of various test methods. The machine base is cast as a whole, the two screws are highly rigid, the wireless remote control of the beam lifting operation, and the test space is adjustable. The upper pressure plate is supported by a spherical surface to ensure uniform force.

Automatic archiving after the test, automatic calculation of maximum force, compressive strength and other performance parameters after the test. The test results (original data and resultant data) can be output in the form of EXCEL format according to the national test standard, which is convenient for users to analyse and research later. The controller load synchronisation output interface allows the load to be synchronised in real time to the strain gauge and DIC-3D data acquisition, making it easy for the user to analyse and process the data without the need for two devices to be operated at a later stage to export the original data.

Figure 10 YAD-2000 electro-hydraulic servo press

Before the test begins the loading surface should first be cleared of debris and the surface of the test block should be checked for smoothness and the appearance should not have obvious defects. Select a smooth front and rear surface as the bearing surface, wipe and measure the area of the bearing surface. Record the area of the bearing surface in the test booklet to facilitate subsequent calculations of uniaxial compressive strength. Place the bearing surface in the centre of the loading table, with the bearing surface of the specimen perpendicular to the axis-forming surface. The test loading equipment is started and when the upper loading surface is close to the small concrete specimen, at the computer control centre, the specimen is zeroed and its bearing surface is positioned so that it is parallel to the platen. The loading process then begins. The loading speed of the tester is set at 0.3mm/min throughout the loading process until the specimen breaks and the loading stops. The test data is recorded and stored by the computer.

The average of the test results from the uniaxial compression test is taken as the average specimen damage load. The averaging process removes values that are clearly out of the norm. The values are brought into the following equation for calculation to obtain the uniaxial compressive strength of the specimen.

$$\sigma_c = \frac{F}{A} \tag{2.1}$$

σ_c-uniaxial compressive strength of the specimen (Pa);

F - ultimate breaking load of the specimen (N)，

A - area of the upper bearing surface (m2).

At the end of the loading test, the average of at least three tests per group is taken as the standard compressive strength of concrete for the current group of test specimens grouped by date.

(a) specimen 1

(b) specimen 2

(c) specimen 3

(g) specimen4

Figure 11 Test results of concrete test blocks strength tests

Its analysis of the test results shows that the damage pattern of the concrete test blocks is mainly dominated by penetrating splitting cracks on both sides, which are also the cause of their loss of load-bearing capacity. Test block 3 and test block 4 correspond to high-strength concrete test blocks, whose test blocks are more completely damaged, as well as the loss of load-bearing capacity occurs more quickly and suddenly, in accordance with formula 2.1 to calculate the uniaxial compressive strength of concrete test blocks. The strengths of the concrete used in the tests were measured to be 30Mpa, 40Mpa, 85Mpa and 125Mpa respectively, according to the requirements of the test program.

2.2.3 Introduction to grouting materials

The grout used in this full-length grouting test is the Chikyu grout developed by Beijing Jiahe Tiancheng New Technology Co. Rather, it has a direction towards high toughness, high damping and high vibration damping while meeting the design requirements in terms of strength. Chikyuu grout uses a unique elasticity technology with the addition of nano-grade polymeric damping and energy absorbing powder materials to provide a damping and vibration damping effect, as well as high crack resistance properties.

The damping and vibration damping performance is 2 to 3 times higher than that of ordinary grout, which can reduce the vibration frequency and noise generated during the operation of dynamic-loaded nuclear equipment, improve the operational accuracy of dynamic-loaded nuclear equipment and prolong the service life of equipment; the impact resistance is more than 3 times that of ordinary cement-based grout, which can withstand higher dynamic and impact loads, and can be used instead of epoxy resin grout for compressors, forging It can be used in compressors, forges, turbines, ball mills, etc. where dynamic and impact loads exist; its toughness is higher than that of ordinary cementitious grouts and epoxy resin grouts, and the bending toughness test shows a cracked and continuous damage pattern. Ordinary cement-based grout and epoxy resin grout fracture quickly after cracks appear, showing brittle damage, while polymer damping grout can continue to bear the load after cracks appear, showing toughness damage. The dual effect of plastic expansion and hardening expansion ensures an effective load bearing surface, ensuring precise positioning and permanent balance of the equipment installation; the superior anti-cracking properties effectively reduce the generation of harmful cracks.

Table 1 Grout technical specifications and measured results

Test items		Actual results	Technical specifications
Mobility	Initial mobility	300	≥290
Vertical expansion rate（%）	3h	0.12	0.1~3.5
	24h vs. 3h Difference in expansion	0.08	0.02~0.5
Compressive strength（Mpa）	1d	26	≥20
	3d	50.3	≥40
	28d	72.8	≥60

2.3 Application of anchor cable preload and full length grouting process

The anchor cable tensioner is used to apply preload to the anchor cable to tighten the test piece. With a maximum pressure of 70 MPa and a high pressure flow rate of 2.2 L/min, the Anchor Tensioner is simple, efficient and safe to operate. On this basis, the anchor cable tensioner can then apply further force to achieve a pre-set preload value.

Figure 12 Anchor cable tensioners

The anchor cables are first tensioned on both sides and the preload fixed in the test plan is applied. After the preload has been applied, the pre-poured concrete is drilled. The concrete test blocks are drilled at the geometric centre on both sides and the grout holes are drilled at the quarter points on both sides for the middle concrete test block. After drilling, the full length of the anchor cable is grouted through the grout holes drilled in the top of the test blocks on both sides. Then after a further 3 days of complete resting and setting, by which time the anchor has reached the required strength, in accordance with the grout instructions and the measured strength. A full length grouted anchor shear test is then carried out.

Figure 12 Full-length grouting process

2.4 Test program

(1) Different preloads

Determine the type of anchor cable to be fixed and the strength of the test block, and set different preload gradients in a targeted manner. For anchor ropes of 21.6 mm diameter and 1 x 7 construction, set a preload gradient of 0 kN, 40 kN and 100 kN. For anchor ropes of 21.8 mm diameter, 1 x 19 construction, set a preload gradient of 0 kN, 100 kN, 200 kN. For a 22mm diameter, hollow grouted anchor cable, two different preloads of 0kN and 100kN were set. The effects of the different preloads on the shear mechanical properties and anchorage behaviour of the full-length grouted anchor ropes were then compared and analysed separately.

(2) Different concrete test block strengths

At different concrete strengths, the shear stiffness, friction factor and shear stiffness of the shear joints of the full-length grouted anchor cable shear system vary. This can have an effect on the shear performance of the anchor cable. Different concrete specimen strengths are used to simulate the different soft and hard surrounding rocks in the actual project. The test results are then tailored to the actual project. The strengths of the test blocks were 30Mpa, 40Mpa, 85Mpa and 125Mpa for normal concrete and high strength concrete respectively, and then the anchor cable type and preload were determined and the effect of changing the strength of the surrounding rock on the anchorage performance of the full length grouted anchor cable was compared and analysed.

(3) Different types of ropes

In this test, the number of anchor strands can be divided into 1×7 and 1×19 structural anchor ropes, of which 1×7 structural anchor ropes can be divided into 17.8mm and 21.6mm in diameter. The 1×19 structural anchor cable is of the 21.8mm type. A hollow grouted anchor cable with a diameter of 22mm was added to the design as the whole test was grouted. A total of four cable types were used. The effect of the different cable types on the overall anchorage effect of the full-length grouted anchor system was analysed individually.

2.5 Summary

This chapter highlights the anchor cable shear test system and workflow principles and prepares and tests the mechanical properties of some materials prior to the formal shear test, and develops a test plan for the subsequent full-length grouted anchor cable shear. The thesis is a summary of the previous research results and shows that the independently designed anchor cable double shear test system is advanced and practical. The mechanical parameters of the relevant test materials will have an influence on the results of the subsequent shear tests, and also pave the way for the analysis of the subsequent shear test results.

A total of four types of anchor cables were used for the full-length grouted anchor cable shear test: 1 x 7 anchor cable with a diameter of 17.8 mm, 21.6 mm and 1 x 19 anchor cable with a diameter of 21.8 mm, and a grouted anchor cable with a diameter of 22 mm. Different preloads were applied to the different types of anchor cables. Four types of concrete test blocks of 30Mpa, 40Mpa, 85Mpa and 125Mpa were used to simulate three different strengths of the surrounding rock in the actual roadway support project. In addition the strength of the grout used for the full length grouting was kept constant and the standard strength after three days of curing was 40Mpa.

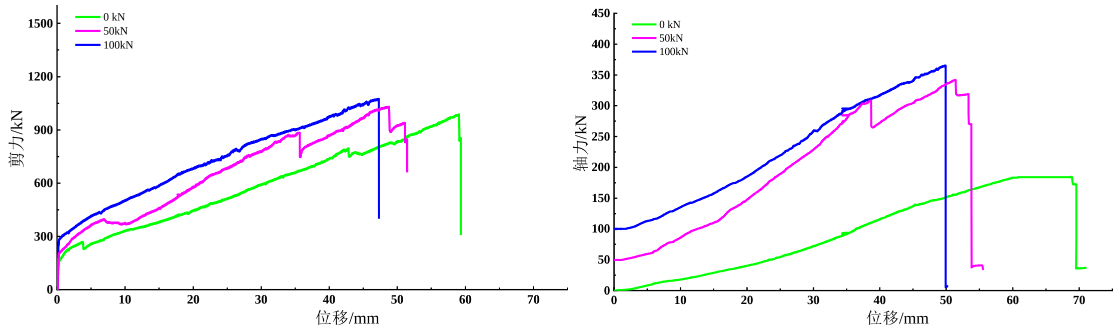
3 Analysis of full length grouted anchor cable shear test results

This chapter builds on the shear tests carried out in the previous section. The test results of the data collected are analysed. The relationship between shear, axial force and displacement of full-length grouted anchor cables is complex and requires a combination of factors to be considered. The pattern of shear and axial forces in full-length grouted anchor cables can vary under different influencing factors. For example, under higher preload and stronger rock conditions, the shear and axial forces of full-length grouted anchor ropes will increase. For different types of ropes, the pattern of shear and axial forces will vary. The influence of each influencing factor variation on the reinforcement mechanism of full-length grouted anchor ropes on jointed rock masses is summarised.

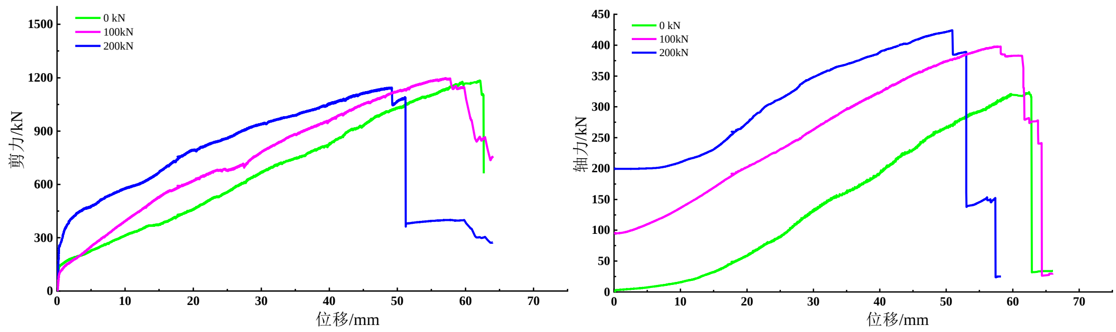
3.1 Analysis of shear test results

3.1.1 Anchor cable shear force-displacement curve

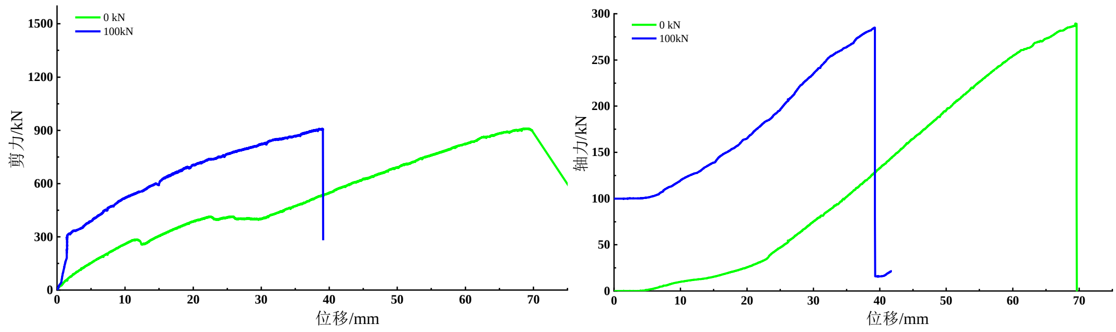
The shear test of the full length grouted anchor cable was successfully carried out according to the shear scheme design in Chapter 2. Before the test started, the experimental apparatus was installed and preload applied, this was to ensure the accuracy and reliability of the test. The loading device was then activated for test loading and the overall test was loaded at a displacement loading rate of 1mm/min. This meant that the test device was moved 1mm per minute to achieve a gradual application of shear force. During the test, the test data needs to be monitored and recorded in real time for subsequent analysis and research. Upon completion of the test, the test set-up and materials need to be checked and evaluated to determine the accuracy and credibility of the test results. Changes in anchor cable shear, axial force and displacement are collected in a timely manner by the data acquisition device until the anchor cable on one side of the joint face fails in shear rupture and loses shear resistance. By analysing the shear force, axial force and displacement data collected, the shear force and axial force with displacement were plotted for anchor ropes with a diameter of 21.6 mm for 1 x 7 structures and 21.8 mm for 1 x 19 structures and 22 mm for hollow grouted structures, for example, at a concrete strength of 50 MPa, and at different preloads.



(a) 1 x 7 construction, 21.6 mm in diameter



(b) 1 x 19 construction, 21.8 mm in diameter



(c) Hollow grouted construction, 22mm in diameter

Figure 13 Anchor cable force displacement curve

3.1.2 Anchor cable shear shear force and axial force variation law

As can be seen from the curves of shear force and axial force from the shear test results, the change in shape of both the shear force and axial force versus displacement curves can be roughly divided into three parts. As an example, the curve of a commonly used 19-strand, 21.8mm diameter anchor cable with an applied preload of 100kN is used to plot the change in shear force versus axial force

The analysis shows that the shear force can be divided into three phases: the initial overall shear resistance phase, the anchor cable shear deformation phase and the anchor cable breakage phase.

The first stage is the initial overall shear resistance stage, where the system needs to overcome the frictional force at the initial jointing surface. The magnitude of the shear force at this point satisfies the Moore-Cullen criterion. With the application of the initial preload, the normal stress at the structural face is increased and the initial shear stiffness of the joint face is improved. Due to the mechanical occlusion between the anchorant and anchor cable and the adhesive effect with the test block, a complete load bearing system is formed under the preload force. This results in a further increase in the overall shear strength of the system.

The second stage is the anchor cable shear stage, when the overall shear strength of the system is mainly provided by the anchor cable, which starts to deform, forming a plastic deformation area, while the shear strength of the whole specimen is increased due to the action of the anchor cable, i.e. the anchor cable starts to play its role of support and reinforcement. The nodal shear surface continues to misalign until the shear force of the anchor cable reaches its peak. Extrusion damage occurs at the contact surface orifice, which is flared.

The third stage is the anchor cable breakage stage, where the anchor cable breaks soon after reaching the peak shear point. As the test model cannot control absolute symmetry, the anchor cable generally starts to break from one side and the breakage will last for a certain period of time.

The analysis shows that the process of axial force change can also be divided into three stages corresponding to the shear force: the continuous stabilisation stage, the smooth rise stage and the rapid slip stage.

The first stage is the continuous stabilisation stage. Initially, for the full-length grouted anchor cable, the axial force of the anchor cable is equal to the initial applied preload due to the frictional force of the joint surface and the mechanical bite of the anchor cable and the anchor fixing agent. At this point the anchor cable is deformed elastically and the initial shear stiffness of the system increases due to the initial preload. Therefore, the initial shear displacement is very small. The anchor cable mainly plays the role of a "pin".

The second stage is the steady rise stage, when the shear stiffness of the system is mainly provided by the anchor cable, which produces a large plastic deformation during the process of shearing until it enters the strengthening stage. Due to the large deformation of the anchor cable at this point, in addition to the support and reinforcement provided by the anchor cable, the anchor cable is also able to withstand the axial force of the specimen during the shear phase, i.e. the anchor cable begins to exert its axial restraint effect. Therefore, as the shear displacement of the specimen increases, the axial force of the anchor cable also increases, and this growth trend is usually linear. When the axial force of the anchor cable gradually increases and reaches its peak point, the specimen has entered the strengthening phase. At this point, the axial force of the anchor cable has reached its maximum load carrying capacity and the support and reinforcement provided by the anchor cable has reached its maximum value. The shear strength of the specimen has also been further increased by the restraining effect of the anchor cable.

The third stage is the rapid slip stage, when the axial force of the anchor cable gradually increases and reaches its peak point, the specimen has entered the strengthening stage. At this point, the support and reinforcement provided by the anchor cable has reached its maximum value. As the specimen is subjected to continuous shear loading, the anchor cable will eventually break and fail. During this process, the stress state within the anchor cable will change rapidly, resulting in a rapid decrease in axial force until failure. At the same time, the specimen will also be destabilised and damaged with the anchor cable failure.

3.2 Analysis of anchor cable fracture and enclosure damage patterns

3.2.1 Analysis of anchor cable damage patterns

In a jointed rock mass, the anchor cable undertakes the important task of shear resistance, which enhances the overall stability and load-bearing capacity of the rock mass by interacting with the jointed face and dispersing the shear forces on the jointed face to the anchor cable. The anchor cable has a certain bending stiffness in the tensile state in the jointed rock mass. When the shear load on the anchor cable exceeds a certain limit, the anchor cable will undergo a certain degree of bending deformation, thus spreading part of the shear force to the joint surface and reducing the shear strength of the joint surface. Figure 14 shows the damage fracture form of the anchor cable and the rock section at the end of the test.

(a) Shear breakage of cables

(b) Bending damage of cables

(c) Anchor cable shear section

Figure 14 Diagram of damage to anchor cable at joint face

The shear fracture of the anchor cable can be observed by looking at the shear fracture of the anchor cable, which can be divided into three types of fracture, namely shear damage, tensile damage and combined tensile and shear damage. Shear damage is typically characterised by shear forces on the rope body, with the fracture being a smooth shear surface. A pure shear fracture of an anchor cable is usually characterised by an inclined surface between the two fracture surfaces, with no obvious signs of tensile or compressive deformation on the fracture surface. Tensile damage is characterised by the fact that the tensile fracture of the anchor cable usually shows a smooth metal surface, often with some fine granular traces along the fracture direction, due to the tearing of the metal particles on the surface of the anchor cable by tensile forces during the stretching process. The fracture surface exhibits a high gloss metallic lustre, often appearing silvery white or grey, with a high reflectivity. In addition, minor defects such as small cracks, air bubbles, inclusions, etc. may appear on the tensile fracture of the anchor cable, usually due to damage during the preparation or use of the material. Taken together, the tensile fracture of an anchor cable usually exhibits characteristics such as smooth and smooth, no visible scratches, silvery white or grey. Combined tensile-shear damage has both of these characteristics and is a form of damage resulting from the coupling of axial and shear forces.

3.2.2 Analysis of the damage pattern of concrete test blocks

Concrete integrity is better when the shear load is low, and when the load is applied to a certain level, the mix This is because when the shear load increases to a certain level, the shear action of the anchor cable at the orifice creates a stress concentration that causes the concrete to rupture at that location. Despite the rupture, the concrete continues to be loaded until the anchor cable fails by breaking, as it is placed in a steel mould. The load-displacement curve during shear is characterised by typical concrete fracture behaviour, where the shear load increases with displacement until the concrete undergoes rupture. Prior to rupture, the load curve is usually smooth, whereas after rupture, the load curve usually fluctuates to varying degrees due to abrupt changes in the shear load caused by a breach in the integrity of the concrete. In addition, the steel mould continues to provide support and restraint in this situation, thus allowing the concrete test block to continue to withstand shear.

Figure 15 Concrete damage patterns

3.3 Analysis of different influencing factors

3.3.1 Preload influence

Anchor cables are widely used in coal mine roadway support, where preload has an important role to play in reinforcing the nodal structural face of the additional anchor cable support, and has been proven in actual engineering practice. However, the actual amount of preload applied needs to be considered in the light of the specific engineering conditions of the roadway support, the characteristics of the jointed structure, the desired anchorage effect and other factors, in order to achieve the best economic results.

In order to determine the effect of preload on the anchorage effect of full length grouted anchor cables. In this experiment, a large number of tests were carried out to determine the shear resistance of three common types of anchor ropes as influenced by the preload force, under the premise that the strength of the surrounding rock was determined to be 50Mpa, and different preload forces were set. The types of anchor ropes are 21.8 mm diameter, 1 x 19 structural anchor ropes, 21.6 mm diameter, 1 x 7 structural anchor ropes and 22 mm diameter grouted anchor ropes, which are commonly used for coal mine roadway support in China. The preload is applied at 30% to 60% of the tensile yield limit to avoid fracture of the anchor during tensioning and application of the preload, which may affect subsequent tests. The preload rate is 1 mm/min. The effect of the preload on the reinforcement of the jointed rock mass during shearing and the deformation and force characteristics of the anchor cable and concrete specimen after shearing are analysed in depth.

Detailed statistics on the peak shear force, peak axial force and shear displacement at breakage for different structures of anchor cables at different preloads during the shear test were made and the statistical process is shown in Table 3.1. It can be concluded from the data in the table that the change in peak shear force is not significant with increasing preload, indicating that increasing preload is not significant in improving the overall shear strength of the system. For the grouted anchor cable (22mm diameter), a preload of 100kN was applied and the peak shear displacement of the system was significantly reduced to a large extent, by 35.4%. For the 1 x 19 structure with a 21.8mm diameter anchor cable and the 1 x 7 structure with a 21.6mm diameter anchor cable, applying a preload of 100kN reduced the peak shear displacement of the joint by 8.5% and 16.7% respectively.

Table 2 Statistics of shear test results at different preload

Type of cable	Rock strength/MPa	Preload/kN	Peak shear/kN	Peak axial force/kN	Breaking shear displacement/mm
1×7-21.6	50	0	988.2	295.4	60.1
	50	40	1029.8	340.5	54.2
	50	100	1075.1	364.7	51.8
1×19-21.8	50	0	1183.6	286.2	60.6
	50	100	1197.3	402.8	57.1
	50	200	1089.1	405.9	55.4
Grouting-22	50	0	910.2	288.8	69.2
	50	100	908.1	284.1	44.7

In the early stages of shear, the relative misalignment between the surrounding rock joints is poorly controlled by smaller preloads compared to larger preloads. Increasing the preload will result in a greater contribution to the axial force during anchor failure, which will be reflected in the test results as more of the cable being pulled off. For a 21.8 mm anchor cable, for example, the peak axial force with a preload of 200 kN was 41.8% greater than the peak axial force without preload applied. This indicates that the axial force plays a greater role in the final anchor cable breakage. For the grouted anchor cable of 22mm diameter, increasing the preload force, the contribution of the shaft force to the final breakage of the anchor cable is not significant.

From the analysis of the force change diagrams of the anchor ropes during shear in Figures 3.3-3.5, it can be seen that the overall shear stiffness of the system is constantly changing with increasing shear displacement during shear. In order to investigate the specific role of preload in the reinforcement of jointed rock masses by full-length grouted anchor cables, it is of great significance to analyse the mechanical parameters of the system such as initial shear stiffness and late shear stiffness variation during shear at different preloads, the statistical results are shown in Table 3:

Table 3 Statistics of shear test results at different preload

Type of cable	Rock strength/MPa	Preload/kN	Initial shear stiffness/kN/mm	Post-shear stiffness/kN/mm
1×7-21.6	50	0	35.8	15.6
	50	40	39.7	25.6
	50	100	55.6	23.5
1×19-21.8	50	0	39.7	21.3
	50	100	58.7	19.2
	50	200	120.8	18.7
Grouting-22	50	0	26.8	15.4
	50	100	58.4	18.5

From the table it can be concluded that increasing the preload has little effect on the later shear stiffness of the system. For a 1 x 19 structure with a 21.8 mm diameter anchor cable, increasing the preload from 0 kN to 200 kN will instead reduce the later shear stiffness by 12.2%. The main reason for this is that increasing the preload will cause the stronger anchor cable to yield earlier, thus reducing the later shear stiffness of the 21.8 mm diameter cable. Increasing the preload has a significant improvement in increasing the initial shear stiffness of the system, for a 1 x 7 structure with a 21.6 mm diameter anchor cable. Increasing the preload from 0kN to 100kN increased the initial shear stiffness of the system by 55.3%. For the analysis of the grouted anchor cable 22mm, the initial shear stiffness with 100kN applied was 117.9% greater than the initial shear strength without preload.

Analysis of the curves shows that increasing the preload has a significant effect on the initial shear strength of the structural face of the joint. For between the rock contact surfaces, increasing the preload is equivalent to increasing the structural face normal force, and according to Cullen's friction law, there is a degree of increase in the initial sliding friction of the structural face of the joint, so the initial shear stiffness of the joint increases with the increase in anchor cable preload. Increasing the preload of the anchor cable is beneficial to the control of the initial shear misalignment of the jointed rock.

3.3.2 Concrete strength influence

In actual roadway support projects, in the face of complex geological conditions, in order to simulate different strengths of the surrounding rock, such as hard rock, medium hard rock, soft rock, etc.. When doing indoor tests, multiple sets of concrete of different strengths are produced for comparison tests. The change in strength of the concrete will cause the friction angle, normal stiffness and tangential stiffness of the joint surface to change. There is also a degree of influence on the performance of the anchor cable in terms of shear resistance. In order to investigate the effect of different concrete strengths on the anchorage performance of full-length grouted anchor ropes, anchor ropes of 1 x 19 structure with a diameter of 21.8 mm were used to study the shear performance of test blocks with strengths at 30 MPa, 40 MPa, 85 MPa and 125 MPa at a preload of 200 kN.

The shear test results for full-length grouted anchor cables at different concrete strengths with respect to peak shear force and peak axial force and their corresponding shear displacements are shown in Table 3.3. The relationship between the specific peak shear force and peak shear displacement for different test block strengths is shown in Figure 3.11. The corresponding peak shear displacement for a test block strength of 125 MPa was 30 mm and the peak shear force was 875.0 kN, while the corresponding peak shear displacement for a test block strength of 30 MPa was 83 mm and the peak shear force was 1313.3 kN. The peak shear displacement was relatively reduced by The peak shear displacement was relatively reduced by 63.8% and the peak shear force was relatively reduced by 33.4%.

Table 4 Statistics on the results of shear tests at different concrete strengths

Type of cable	Rock strength/MPa	Preload/kN	Peak shear/kN	Peak axial force/kN	Breaking shear displacement/mm
1×19-21.8mm	30	200	1312.66	446.47	82.81
	40	200	1131.44	159.18	53.38
	85	200	980.54	380.26	32.53
	125	200	875.03	299.61	19.525

The statistics of the overall shear stiffness and other relevant mechanical parameters of the nodular rock shear full-length grouted anchor cable anchorage system for different surrounding rock strengths are shown in Table 5. At a preload of 200 kN, for a 1 x 19 structure with a 21.8 mm diameter anchor cable, increasing the strength of the test block results in a corresponding reduction in the shear displacement of the system, corresponding to a faster shear break failure of the anchor cable. As the test block strength increases, it can be seen from the table that the higher the test block strength, the higher the initial shear stiffness of the corresponding system in shear. The initial shear stiffness of the 1 x 19 structure with a 21.8 mm diameter anchor cable at a test block strength of 125 MPa is 232.5% higher than that at 40 MPa. It can also be seen that increasing the strength of the rock mass also has a beneficial effect on the later shear stiffness, for example, the later shear stiffness of the 1 x 19 structural diameter anchor cable of 21.8 mm is 75% greater at a block strength of 85 MPa than at 30 MPa. This indicates that increasing the test block strength has a definite effect on improving the overall shear stiffness of the system.

Table 5 Statistics of system shear parameters at different concrete strengths

Type of cable	Rock strength/MPa	Preload/kN	Initial shear stiffness/kN/mm	Post-shear stiffness/kN/mm
1×19-21.8mm	30	200	79.05	11.89
	40	200	89.97	15.72
	85	200	230.70	20.83
	125	200	296.27	30.11

3.3.3 Influence of the type of anchor cables

Five different types of anchor ropes were selected for this test: 1 x 7 anchor ropes with diameters of 17.8mm and 21.6mm; 1 x 19 anchor ropes with diameters of 21.8mm; and hollow grouted anchor ropes with diameters of 22mm. In order to investigate the effect of different cable types on the anchorage performance of the jointed rock, five different cable types were selected and tested in shear with a pre-stress of 100 kN and a concrete strength of 50 MPa.

Analysis of the shear displacement curves for the different types of anchor ropes shows that the peak shear force during shear is also highest for the 1 x 19 anchor rope with a structural diameter of 21.8 mm. For the 1 x 7 anchor cable with a diameter of 17.8 mm, the peak shear displacement is the largest compared to the other anchor cables. For the 22 mm diameter grouted anchor cable, the 7 strand anchor cable with a diameter of 21.6 mm and the 19 strand anchor cable with a diameter of 21.8 mm, the overall shear stiffness of the joints is essentially the same, while the later shear stiffness has some variability.

Table 6 Statistics on the results of shear tests with different cable types

Type of cable	Rock strength/MPa	Preload/kN	Peak shear/kN	Peak axial force/kN	Breaking shear displacement/mm
1×19-21.8	50	100	1196.92	406.25	57.735
1×7-21.6	50	100	1075.18	388.53	50.5445
1×7-17.8	50	100	885.36	297.32	60.395
Grouting-22	50	100	908.13	287.68	44.71

Table 7 Statistics on the shear parameters of the system with different cable types

Type of cable	Rock strength/MPa	Preload/kN	Initial shear stiffness/kN/mm	Post-shear stiffness/kN/mm
1×19-21.8	50	100	127.33	18.55
1×7-21.6	50	100	176.42	17.32
1×7-17.8	50	100	104.48	12.11
Grouting-22	50	100	111.81	15.67

Changing the type of cable has little effect on the initial shear stiffness of the system. The anchor cable of 1 x 7 structure with 21.6mm diameter has the highest initial shear stiffness of 176.42kN/mm under the same conditions, while the anchor cable of 1 x 7 structure with 17.8mm diameter has the lowest initial shear stiffness of 104.48kN/mm. 21.6 mm is 68.9% greater than the initial shear stiffness of 17.8 mm. The 1 x 19 anchor cable with a diameter of 21.8 mm had the highest post-shear stiffness of 18.55 kN/mm, which was 53.2% greater than the 1 x 7 anchor cable with the lowest post-shear stiffness of 17.8 mm. The initial shear stiffness and late shear stiffness of the slurry injected anchor cable were between the 17.8mm diameter and 21.6mm diameter 1 x 7 structure anchor cables. It can be concluded from the analysis that increasing the number of strands and the diameter of the cable can improve the overall shear stiffness of the system to some extent.

3.4 Summary

In this chapter, by conducting shear tests on full-length grouted anchor ropes in the laboratory, the damage pattern of the anchor ropes and the surrounding rock mass, as well as the change of anchor rope axial force and shear force-displacement relationship are derived, and the conclusions are as follows

(1) The change of shear force-displacement during the shear process is divided into three stages: the pre-shear stage, the anchor rope shear deformation stage and the anchor rope breakage stage; due to the mechanical occlusion between the anchor and the anchor rope and the adhesion of the test block, a complete bearing system is formed under the action of preload, which makes the anchor rope play the shear role at the early stage of shear deformation of the full-length grouted anchor rope and improves the anchor rope (1) The overall shear strength of the anchor cable and the anchor joint

(2) At the beginning of shear deformation, the anchor cable mainly acts as a "pin", which means that the axial load on the anchor cable increases slowly and the corresponding shear force also increases slowly. As the shear force increases, the anchor rod begins to act as an axial restraint, causing the axial load on the anchor cable to increase at a faster rate, with a tendency to increase at a uniform rate. When the axial load reaches its peak point, the anchor cable will break, at which point the axial load will fall rapidly, which will also result in a rapid decline in the corresponding shear force, showing a rapid downward trend.

(3) Analysis of the anchor cable breakage form, the anchor cable breakage form, observe the section can be seen, the anchor cable damage shape is "Z" shear deformation, anchor cable shear process, the anchor cable on the joint rock body to weaken the restraint effect, the overall strength of the joint rock body decreased, resulting in the surrounding rock extrusion damage, forming a hole flare.

(4) Increasing the preload of the anchor cable can improve the initial shear stiffness of the system, and increasing the preload has little effect on the peak shear force of the different anchor cables that finally yield gradually. The shear displacement of the joints when the anchor cable reaches peak shear decreases as the preload force is increased. This indicates that increasing the preload reduces the ductility of the overall support structure.

(5) By increasing the strength of the test block, the shear displacement of the system will be reduced to a corresponding degree, corresponding to the anchor cable will fail in shear more quickly. The higher the strength of the test block, the faster the shear force rises in the shear process of the corresponding system, indicating that increasing the strength of the test block has a certain enhancement effect on improving the overall shear stiffness of the system. The weaker rock strength has a large deformation at the concrete orifice, and the damage at the orifice is more severe, corresponding to a larger shear deformation of the structure as a whole.

(6) For different types of anchor ropes, the initial shear stiffness is greatest for 1 x 7 anchor ropes of 21.6mm diameter under the same conditions, and the later shear stiffness

is greatest for 1 x 19 anchor ropes of 21.8mm diameter. Increasing the number of strands and diameter of the cable can increase the overall shear stiffness of the system to some extent.

4 Analysis of the anchoring effect of nodal rock anchor cables

4.1 Numerical simulation of the interaction between a jointed rock mass and an anchor cable

Numerical simulation is a method of analysing and solving real engineering problems through mathematical methods and computer technology. Compared with traditional experimental and empirical methods, numerical simulation has the following advantages: cost saving: traditional experimental methods require a lot of experimental equipment, manpower, material resources and time, while numerical simulation only requires a computer and the corresponding software to complete the simulation, which greatly saves costs. Improved efficiency: traditional experimental methods require repeated experiments, while numerical simulation can produce simulation results at once, greatly improving research efficiency. Protecting the environment: traditional experimental methods often require a large amount of resources, whereas numerical simulation does not require experiments and can avoid environmental impacts. Improved accuracy: Numerical simulations can use high-precision mathematical methods and computer technology to produce more accurate results. Greater safety: some experiments can be dangerous, and numerical simulation can avoid these potential safety risks. In summary, numerical simulation is an efficient, accurate, economical, environmentally friendly and safe method of solving engineering problems and can be widely used in engineering design, optimisation and research.

As the shear tests of anchor cables carried out indoors themselves have some drawbacks due to the inability to ensure absolute accuracy by hand as well as by instrumentation, for example, the absolute strength of concrete test blocks and the degree of crack development at the joint surface cannot be guaranteed to be absolutely identical. The shear force applied by the press does not accurately reflect the exact forces on the anchor cable body, nor does it allow for the observation of changes in the internal anchor cable and the surrounding rock mass. Therefore, this chapter analyses the overall force characteristics of the anchor cable and the interaction with the surrounding rock mass by means of numerical simulation.

4.1.1 Introduction to ABAQUS numerical simulation software

(1) ABAQUS Application

ABAQUS is a commercial finite element analysis software developed by Dassault Systems (Dassault). It is widely used in engineering, especially in product design and development in the fields of aviation, automotive, marine, energy and construction. ABAQUS provides powerful simulation and analysis capabilities to simulate and analyze complex structural and material behavior, such as nonlinear materials, large deformation, large deformation, damage, fatigue, etc. It also supports multi-physics field coupling, such as thermal, electrical, magnetic, fluid dynamics, etc. ABAQUS also provides a user-friendly interface to write macros in Python to extend the software functionality. In addition, it supports a variety of solvers, such as standard solver, explicit solver, implicit solver, etc., which can meet different solving needs. In summary, ABAQUS is a powerful, flexible and scalable finite element analysis software that helps engineers and researchers analyze and optimize product designs to improve product performance and quality. the main features of ABAQUS include flexible post-processing, multi-physics field coupling, large deformation/large deformation, material nonlinearity and complex geometry modeling. Its simulation results can often be in good agreement with experimental data and are therefore widely used for engineering design, optimization and validation.

(2) ABAQUS software use

The functional modules of ABAQUS mainly include the following parts:

1) Geometric Modeling Part: according to the model to be modeled in ABAQUS sketch interface or CATIA sketch, and then form the model by stretching and rotating.

2) Dividing Mesh: The mesh of the model to be analyzed is divided, the mesh should be carefully divided, and the number of meshes of the components to be analyzed should be sufficient. Whether the mesh division is accurate and scientific directly affects the convergence of the final calculation results.

3) Property setting: Set the properties of the model, for example, set the material properties to plastic or elastic material, and then set the corresponding compressive strength and yield strength.

4) Establish Assembly: Assemble the different parts previously established into a unified whole according to the requirements.

5) Define the analysis step Step: According to the process of analysis, define how many analysis steps are needed. The accuracy of the analysis step also plays an important role in whether the calculation results can be converged.

6) Interaction Iteraction: Define the contact action between the components, such as defining the friction coefficient, etc.

7) Load boundary Load: Set the boundary conditions of the model and the constraint effect. Ensure the smooth operation of the calculation.

8) Submitting Job: After setting the material properties of the assembly and applying the boundary conditions and constraints, determine the number of analysis steps and submit it to the computer for calculation.

9) Post-processing Visualization: After the settlement, the stress-strain cloud and data are output as required.

4.1.2 Numerical modeling and simulation scenario determination

(1) Establishment of numerical model

According to the size of the concrete test blocks from the laboratory tests in ABAQUS software to establish a model of equivalent size, the model mainly consists of a combination of three side-by-side concrete test blocks, the type of test block components are 3D deformable entities, to establish the same size of the concrete test block model as described in the previous section, to facilitate the comparison of numerical simulation results with the test results to verify the additional establishment of 1 × 19 structural diameter of 21.8 mm anchor cable and the external grouting ring.

(2) Material parameters setting

The relevant mechanical parameters of grout and concrete block and anchor cable materials are referred to the following table 8: set the concrete test block and grout as brittle materials, set the strength of concrete test block as 50Mpa and the compressive strength of grout as 40Mpa.

Table 8 Material-related parameters

Material properties	Anchor cable	Test blocks	Grouting materials
Density（kg/m^3）	7850	2300	2300
Young's modulus（Gpa）	200	30	36
Poisson ratio	0.3	0.18	0.18
Yield stress（Mpa）	1860	——	——

(3) Boundary conditions and application of preload

After drawing the mesh of the assembled and established concrete parts, the boundary conditions are set. In ABAQUS, boundary conditions are used to specify the forces or displacements of certain regions or nodes in the simulation model, thus simulating the occurrence of physical phenomena. Setting boundary conditions allows the simulation results to be more accurate and reflect the behaviour of the real physical problem. During simulation, boundary conditions affect the response of the model and are often a key part of the model, having a significant impact on the accuracy of the simulation results. In ABAQUS, common boundary conditions include: displacement constraints, force constraints, velocity constraints, temperature constraints, etc. Depending on the simulation problem, appropriate boundary conditions can be selected to simulate the occurrence and evolution of physical phenomena. The boundary conditions set for this simulation are shown in Figure 15.

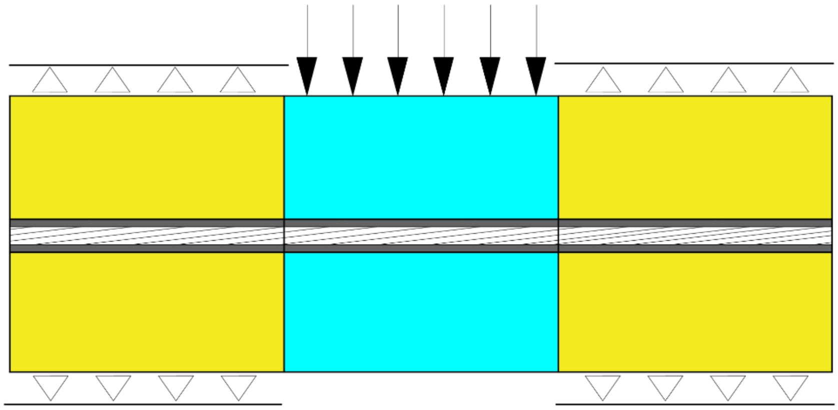
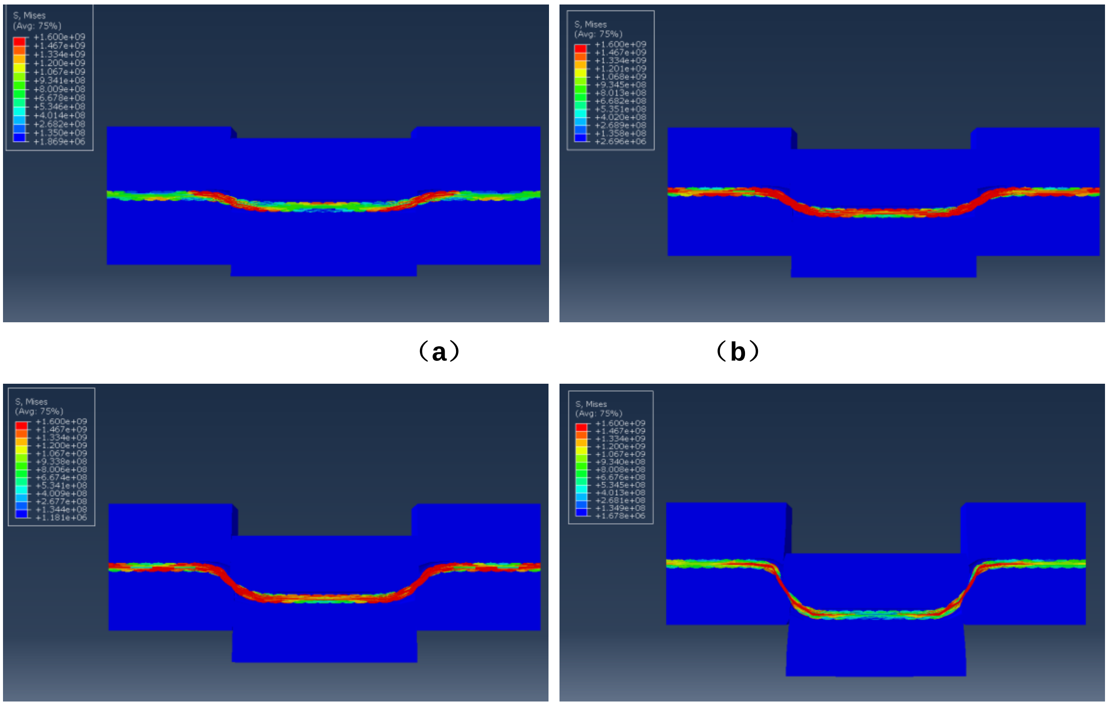


Fig. 16 Boundary conditions

The method of applying preload is the cooling method. The principle of the cooling method for applying preload to anchor ropes. The cooling method is a common method for applying preload to anchor ropes. The basic principle is to preload the anchor cable by exposing it to low temperatures under predetermined tension through the thermal expansion and contraction properties of the anchor cable, causing the anchor cable to contract and deform during the cooling process. Here is a simple procedure to illustrate how to apply preload to an anchor cable using the cooling method: After applying a predetermined tension to the anchor cable, expose it to a low temperature environment. This can be done by using coolants such as liquid nitrogen, dry ice etc. to cool down. After the anchor cable has cooled sufficiently and has developed shrinkage and deformation, it is removed from the cooling environment. After the anchor cable has returned to room temperature, check and adjust the tension to ensure that the required preload has been achieved. It is important to note that when using the cooling method, the appropriate cooling temperature and time should be selected depending on the material and size of the anchor cable and the required preload. Care also needs to be taken to check and adjust the tension of the anchor cable in time after it has returned to room temperature to ensure that it has the required mechanical properties under normal operating conditions. The objective of cooling down the anchor cable to give it the desired preload is achieved by setting an expansion factor for the anchor cable components in the numerical model. The equation used for the cooling method is: $\Delta T = \sigma / E\alpha$, where ΔT is the temperature difference and α is the expansion coefficient. The preload is set to 200 kN.

4.1.3 Overall force characteristics of the anchor cable during shear

After applying a preload of 200kN at both ends of the anchor cable by the cooling method, the stress cloud of the anchor cable is shown in Figure 17 and the overall displacement cloud of the system is shown in Figure 16.



(a) (b) (c) (d)

Fig. 17 Anchor cable stress cloud maps

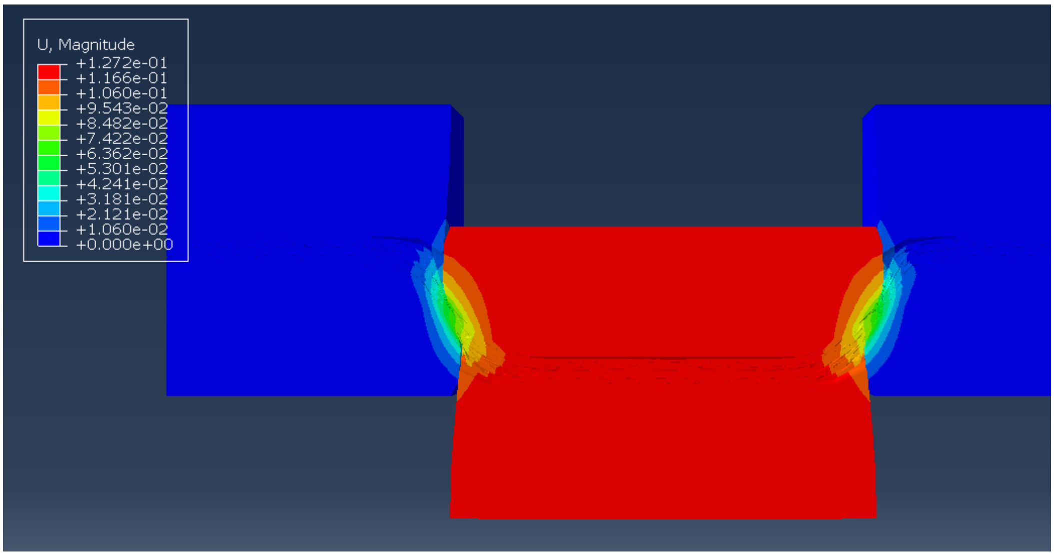
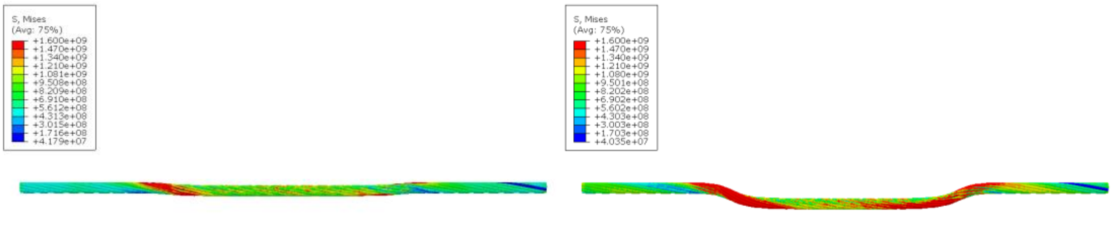


Fig. 18 Anchor cable stress cloud maps

The final shear displacement of the anchor cable can be used to compare the effect of different anchor cable parameters and test block parameters on the shear strength of the system, which can reflect the displacement, deformation and stress distribution of the anchor cable and test block obtained in the shear stiffness simulation of the system can also be used to further analyse the force characteristics and working mechanism of the system. As can be seen from Figures 5.2 and 5.3, the overall displacement of the system is 127 mm. When the full-length grouted anchor cable is first displaced, the stresses and strains at the shear location of the contact surface of the jointed rock are small, and at this time the main joint surface and grout are providing the overall shear strength of the system. As the shear force gradually increases, the grout in contact with the anchor cable begins to break down, as does the stress concentration phenomenon at the orifice, and the stress at the shear location of the anchor cable gradually increases. As the shear force continues to increase. The distal end of the anchor cable has a higher stress due to the compression of the test block. The shear force continues to increase until the anchor cable breaks and fails. A cloud diagram of the overall stress characteristics of the anchor cable is shown in Figure 18.



(a) (b)

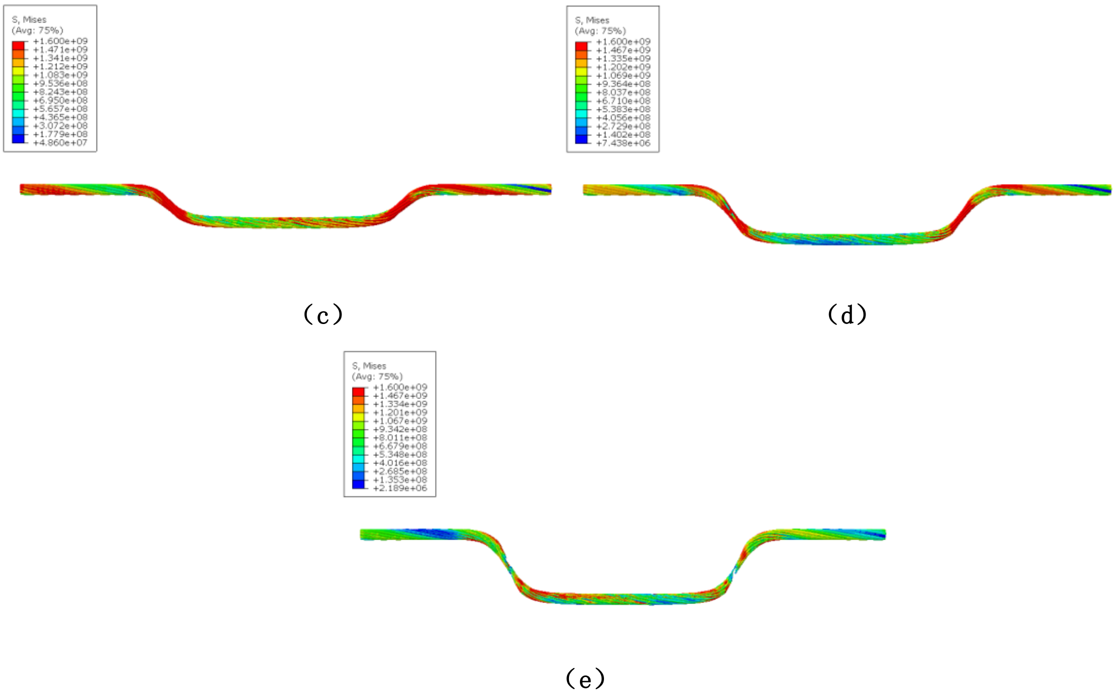
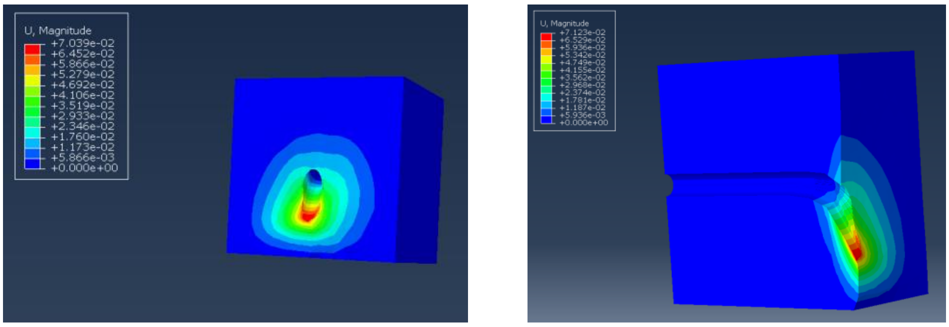


Fig. 19 1×19 The overall force characteristics of the anchor cable with a diameter of 21.8mm

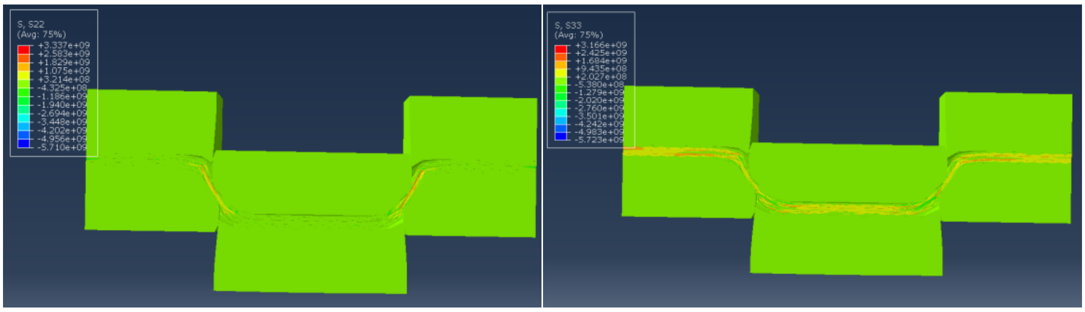
4.1.4 Interaction of the anchor cable with the surrounding rock mass

The interaction between the anchor cable and the grouted surrounding rock is very close. The grout is mainly used to reinforce the surrounding rock and improve its mechanical properties, thus enhancing the support of the anchor cable. After grouting, the adhesion and friction between the anchor cable and the grouted surrounding rock are also enhanced, which can effectively share the anchor cable load and make the anchor cable more evenly stressed. At the same time, the grout surround rock will also produce resistance to the anchor cable, improving the shear stiffness and load carrying capacity of the anchor cable when under stress. Therefore, the interaction between the anchor cable and the grout surrounding rock is complementary, and the two work together to effectively improve the supporting effect of the anchor cable and the shear strength of the surrounding rock. The mechanism of interaction between the anchor cable and the surrounding rock. At the end of the simulation one can clearly see the flared orifice formed by the anchor cable for the orifice at the joint face, as shown in Figure 20. The deformation of the concrete specimen can be clearly seen by cutting the cross-section and the section is shown in Fig 21.



(a) **(b)**

Fig. 20 Deformation of test block orifice



(a) **(b)**

Fig. 21 Test block section

4.2 Anchorage mechanism for knotty rock anchor cables

The results of both the indoor tests and the numerical simulations show that the placement of a full-length grouted anchor cable in a test block with a jointed face increases the shear and deformation properties of the jointed rock mass after the application of preload. The anchorage effect is greatly influenced by the nodal surface in the rock mass, and the anchoring mechanism of the anchor cable is achieved to a large extent by the friction and support forces with the nodal surface. When preload is applied to the anchor cable, friction will be generated on the joint surface. The greater the friction on the joint surface, the greater the shear resistance of the anchor cable. Under the anchoring action, the anchor cable will deform. As the rock material is subjected to forces that produce elastic and plastic deformation, when the anchor cable is deformed, the surrounding rock material will also be deformed. In this way, the anchor cable creates a supporting effect with the surrounding rock mass, increasing the anchorage effect. In addition to the action of the jointing surface, the interaction between the anchor cable and the concrete test block is also part of the anchoring mechanism. The anchor cable can anchor the concrete test block together with the anchor cable and, through the adhesive action with the test block, translate the shear capacity of the anchor cable into the shear capacity of the entire anchorage system.

4.2.1 Analysis of the shear mechanical behaviour of full-grouted anchor cables in jointed rock masses

(1) Theory of the strength of a jointed surface when subjected to shear

A jointed rock mass is a geological form composed of many hard rocks and is characterised by the presence of a number of pre-formed joints or fractures in the rock. These joints or fractures may be caused by factors such as earthquakes, tectonic movement or chemical action. A jointed rock mass is usually composed of blocks of rock with similar rock types and jointing patterns. The morphology of the joints may be parallel, intersecting, stepped or otherwise. The distribution and arrangement of these joints in a rock mass can provide important clues to geoscientists in understanding the movement of the earth's crust and the process of rock formation.

Joints are often used in a wide range of geological and engineering applications, for example in rock mining, underground tunnel construction and geotechnical engineering. By studying the structure and properties of jointed rock masses, the shear strength of the jointed surfaces can be analysed. A better understanding of the strength, stability and viability of the rock can be gained, thus providing valuable information for decision making in these fields. The shear strength of a joint face is the magnitude of the maximum shear stress that the joint face can withstand when a shear force is applied to the joint face, and here the Moore-Cullen equation (Mingrong Shen. et al., 2015) is used to calculate the shear strength of the joint face.

$$\tau = \sigma \tan\varphi + c \tag{4.1}$$

τ - tangential stress;

σ - normal stress;

ϕ - angle of internal friction;

c - cohesion.

During shearing of a jointed rock body, the joint face is deformed normal to the shear force. Specifically, when the joint face is subjected to shear, the rock mass on the joint face begins to slide along the joint face, causing the length of the joint face to change, as well as causing bending and twisting of the joint face. These deformations lead to normal displacement and normal strain of the joint face, which affects the mechanical properties of the joint face. Normal deformation is a very important research element in the study and engineering application of jointed surfaces. Normal deformation is calculated using Equation 4.2

$$U_d = U_0 \tan\phi \tag{4.2}$$

U_d -normal deformation;

U_0 -tangential deformation;

ϕ - Shear expansion angle.

(2) Analysis of anchor cable deformation at the shear joint surface

Determining the forces: Firstly the forces acting on the anchor cable need to be determined, including horizontal forces, vertical forces and shear forces. These forces will produce different stresses and strains on the anchor cable.

Calculating stresses: Stress is the force per unit area and can be calculated by dividing the force applied by the cross-sectional area of the anchor cable. At the shear joint surface, the shear force will result in a shear stress which is in a direction perpendicular to the shear force. Calculating strain: strain is the deformation per unit length and can be calculated by dividing the difference in length before and after the force applied to the anchor cable by the length of the anchor cable. At the shear joint face, the strain in the anchor cable will change because the length of the anchor cable will change as it moves along the shear face. Analysis of deformation: Based on the stresses and strains in the anchor cable, the deformation of the anchor cable at the shear joint face can be analysed. This includes deformations such as bending, twisting and stretching of the anchor cable. The anchor cable body is also deformed with the misalignment of the surrounding rock in a "Z" shape. This is shown in Figure 21

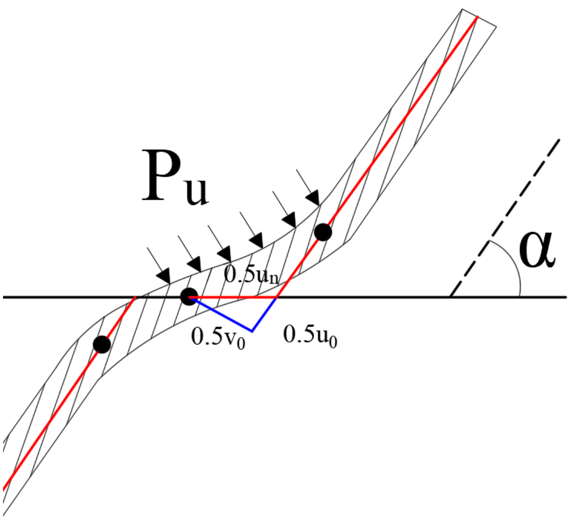


Fig. 22 Schematic diagram of the shear deformation of the anchor cable

4.2.2 Calculation of shear strength at shear joints

The force analysis of a single cable during shearing of a full-length grouted anchor cable is shown in Figure 22. It can be seen that when relative sliding occurs on the structural face of the surrounding rock joints, the anchor cable body is subjected to shear, and additional axial and shear stresses are generated in the anchor cable body at the joints, which have their corresponding components in the shear direction (unfavourable to the performance of shear resistance) and in the reverse shear direction (favourable to the performance of shear resistance) respectively. The shear strength of a jointed rock anchored by an anchor cable consists of two components:

(1) the shear strength of the joint face itself;

Determined by the cohesion and internal friction angle of the surrounding rock itself, it also increases with increasing preload, as the application of preload corresponds to an increase in the normal stress at the structural face. Eq. 4.1 leads to the conclusion that increasing the preload increases the shear strength of the joint face. This contributes to the overall shear strength.

(2) Shear strength of the cable body.

The presence of the anchor cable increases the overall shear strength of the structural system because the anchor cable is subjected to shear forces that generate reaction forces in the axial and shear directions, which counteract the sliding of the structural face of the surrounding rock in the structural system, thereby increasing the overall stability and shear strength of the structural system. The anchor cable ropes will be subjected to shear forces, which will result in component forces in the axial and shear directions that will prevent deformation. This will contribute to the overall shear strength of the structure.

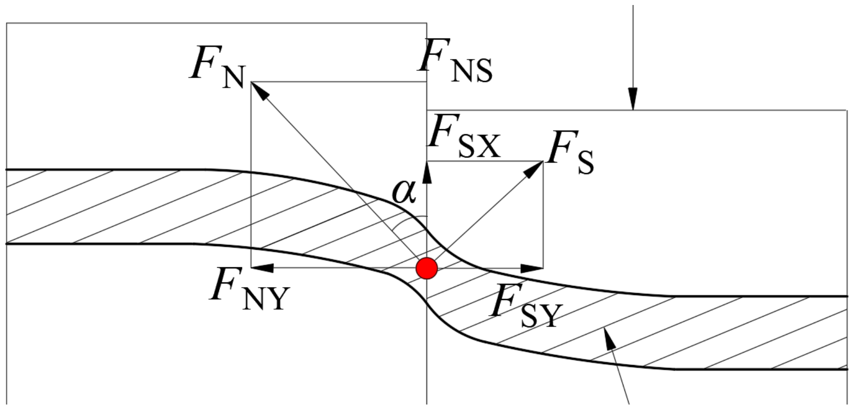


Fig. 23 Diagram of force analysis of anchor cable body

A force analysis of the anchor cable body shows that the shear strength of the anchor cable is given by the formula

$$\tau = \tau_0 + \tau_n + \tau_t \tag{4.3}$$

where each parameter is calculated as

$$\tau_0 = \sigma_0 \tan\varphi + c_0 \cdot$$

$$\tau_n = \frac{F_N}{A}\cos\alpha + \frac{F_N}{A}\sin\alpha \cdot \tan\eta$$

$$\tau_t = \frac{F_s}{A}\sin\alpha - \frac{F_s}{A}\cos\alpha \cdot \tan\eta$$

Where: τ_0 is the shear strength of the surrounding rock joint surface itself; τ_n is the shear strength of the anchor cable body increased by the additional axial force due to the increase in preload; τ_t is the shear strength contributed by the shear reaction force generated by the cable body when the anchor cable body is subjected to shear. σ_0 is the normal stress inside the surrounding rock joint; φ is the angle of internal friction; c_0 is the cohesive force; F_N is the axial force generated during the shearing of the anchor cable; α is the angle between the axial direction and the horizontal direction of the single cable body of the anchor cable; η is the ratio of the cross-sectional area of the anchor cable to the nodal surface.

The analysis of the overall shear strength formula of the anchor cable anchorage joint can be obtained: increasing the preload can increase the overall shear strength, because increasing the preload can increase the reverse stress between the surrounding rock joint surface, which can be derived from the Moore-Cullen formula, thus increasing the shear strength of the surrounding rock joint surface itself. Increasing the preload also increases the axial force of the anchor cable, which indirectly increases the shear capacity of the anchor cable. Increasing the number of strands and the diameter of the anchor cable also increases the shear reaction force and the additional axial force when the anchor cable is subjected to shear, which in turn increases the shear strength of the anchor cable anchoring the jointed rock.

During the interaction between the anchor cable and the surrounding rock, the deformation and damage state of the anchor cable body and the surrounding rock changes as the shear displacement increases, thus affecting the mechanical properties of the joint surface. Therefore, equation 4.3 is only applicable before the anchor cable has yielded and the surrounding rock has not entered the plastic damage stage, for more complex cases further research and analysis is required.

4.3 Summary

(1) From the numerical simulation, it can be obtained that the stress in the shear position of the anchor cable gradually increases during the shear process. As the shear force continues to increase. The distal end of the anchor cable has a higher stress due to the compression of the test block. As the shearing process gradually proceeds, the anchor cable gradually begins to break down due to the extrusion of the surrounding rock mass during shearing. The grout gradually starts to break down, resulting in stress concentrations. The stress in the surrounding rock at the hole opening rises significantly.

(2) The mechanism of the full-length grout anchor cable anchoring the nodular rock mass was investigated using the formula theory, and the contribution of the anchor cable was mainly in two parts: the pinning action in the shear direction and the binding action in the axial direction, and the overall shear strength of the nodular rock mass anchoring was proposed to be divided into three parts: the shear strength of the surrounding rock contact surface itself, the shear strength generated by the preload force applied by the anchor cable, and the shear strength contributed by the reaction force generated by the anchor cable in the shear process. and a brief analysis of the effect of each factor.

5 Conclusion and future research directions

5.1 Conclusion

This thesis takes full-length grouted anchor cable as the research object, and investigates the influence law of preload force, rock strength and cable type on the shear mechanical behavior of full-length grouted anchor cable through indoor test, numerical simulation and theoretical analysis. The influence of corresponding factors on the peak shear strength and shear displacement of full-length grouted anchor ropes, and the anchorage characteristics of nodal rock anchor ropes are obtained. The following conclusions were obtained:

(1) The change process of shear force can be divided into three stages: the pre-integral shear resistance stage, the anchor cable shear deformation stage, and the anchor cable breaking stage; the change of anchor cable axial force corresponds to the change process of shear force, but the change process is divided into: continuous stable stage, smooth rising stage, and rapid sliding down stage according to the trend of curve.

(2) Analysis of the anchor cable breakage form, the damage form of anchor cable body mainly has tensile damage, shear damage and tensile shear composite damage. The shearing process of the anchor cable weakens the restraining effect of the anchor cable on the jointed rock body and reduces the overall strength of the jointed rock body, which leads to the extrusion damage of the surrounding rock and the formation of the orifice flare.

(3) Increasing the preload can significantly improve the initial shear stiffness of the system. Increasing the preload force has little effect on the peak shear force of different anchor cables that finally yield gradually. The shear displacement of the nodal joint when the anchor cable reaches the peak shear decreases with increasing preload. It means that increasing the preload force will reduce the ductility of the whole support structure.

(4) By increasing the strength of the test block, the shear displacement of the system will be reduced to a corresponding degree, and the corresponding anchor ropes will fail in shear more quickly. The higher the strength of the test block, the faster the shear force in the shear process of the corresponding system rises, indicating that increasing the strength of the test block has a certain enhancement effect on improving the overall shear stiffness of the system. The deformation at the concrete orifice with weaker rock strength is large, and the damage at the orifice is more serious, corresponding to the larger overall shear deformation of the structure.

(5) For different types of anchor cables, the peak shear force of the anchor cable is positively correlated with its own tensile strength. The overall shear stiffness of the 22mm diameter hollow grouted anchor cable, the 21.6mm diameter 1×7 strand anchor cable and the 21.8mm diameter 1×19 strand anchor cable are basically the same. The overall shear stiffness of the system can be improved to a certain extent by increasing the number of strands and diameter of the cable.

(6) The overall stress characteristics of the anchor cable and the interaction between the anchor cable and the surrounding rock were obtained by simulating the anchor cable shear process with numerical software, and as the shear process proceeded, the grout began to gradually destroy leading to the stress concentration phenomenon. The stress at the hole of the rock body increases. The shear stress at the shear of the anchor cable keeps increasing. The stress at the distal end also increases to some extent in the later stage.

(7) Theoretical analysis using equations further reveals the anchoring mechanism of the anchor cable in the jointed rock mass, and the contribution of the anchor cable is mainly in two parts: the pinning action in the shear direction and the binding action in the axial direction, and the rock mass is divided into two parts along the shear direction of the anchor cable: the linear region and the plastic deformation region, and the deformation and load relationship of each is analyzed. The overall shear strength of the nodal rock anchorage is proposed, which is divided into three parts: the shear strength of the surrounding rock contact surface itself, the shear strength generated by the preload force applied to the anchor cable, and the shear strength contributed by the reaction force generated by the anchor cable during the shear process, and the influence of each factor is briefly analyzed.

5.2 Shortcomings and outlook

(1) The full-length grouted anchor cable shear test model conducted in this thesis does not take into account the anchorage angle factor, resulting in some differences between the shear force of the anchor cable and the actual engineering support, and the nature of the surrounding rock on both sides of the joint surface has exactly the same strength, which is somewhat different from the geological conditions of the engineering site. To a limited extent, the shear characteristics of the full-length grouted anchor cable are revealed.

(2) The test process uses constant displacement rate loading, which is a static load. However, in actual engineering, anchor ropes can also break in mines where impact

ground pressure occurs. Further research can be done on the shear resistance of anchor ropes under impact loading.

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