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Study on the Application of Fibre Reinforced Polymer Bars in Civil Engineering

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The steel anchor reinforcement technology is an important means of geotechnical engineering reinforcement. It can fully mobilize and improve the soil's strength and stability, narrow the dimension of structures, and reduce its weight, significantly saving the engineering materials. With the development and application expansion of anchoring techniques, steel bolt is almost applied in all aspects of civil construction field, such as slope, excavation, mine, tunnel, dam, underground engineering, airports, ports, retaining wall, abutment anchorage and so on engineering constructions and transformations. In this paper, the bearing capacity of glass fibre reinforced polymer (GFRP) and the bond strength in the cement mortar are discussed, and compared with steel bolt. In this paper, the test results of GFRP anchor and steel anchor in the concrete block and rock block in the laboratory and in the field are described. In the experiment, four kinds of GFRP anchors and two kinds of steel anchors were installed in the mass concrete block and the field rock block. The test results showed that the bond strength of GFRP bolt is close to that of steel bolt, and the sliding of GFRP bolt is higher than that of steel anchor, which is mainly due to the lower elastic modulus of GFRP bars.

1. Introduction

The application of soil anchor in civil engineering is more and more, and they are also used in temporary and permanent structural engineering to ensure the reliability of the structure (Tao, 2014). Such as: landslide, retaining walls, piers, channels, underground caverns, reinforced concrete foundation and rock walls and so on, this kind of anchor is also used to reinforce and repair the existing structures. In general, the grouted anchor is to insert a rod into a well-drilled concrete or rock hole, and then it is filled with mud. At present, the fibre reinforced polymer bars include aramid fibre reinforced plastic (AFRP), carbon fibre-reinforced plastics (CFRP), glass-fibre-reinforced plastic (GFRP) and so on reinforced plastic products (Adam e tal., 2015; Said et al., 2016). FRP has many advantages, such as corrosion resistance and chemical erosion, high specific strength, electromagnetic neutrality and so on. These advantages can improve the durability of the anchor and the convenience of transportation, and facilitate the construction and installation, etc. In addition, in the production process, the optical fibre sensors and other components can also be placed in the FRP bar, to make a permanent testing for the FRP anchor. However, the experimental research on FRP grouting bolt is very limited. For instance, test results on FRP bolt and cement mortar bond strength and drawing characteristics, resistance endurance strength and so on in alkaline environment and are very limited (Zhang et al., 2016). In this paper, the bond strength and bearing capacity of glass fibre reinforced plastic (GFRP) grouting bolt are studied mainly. The main purpose of this paper is to study the bond characteristics and drawing properties of GFRP grouting anchor. The bearing capacity, the bond strength, the load-slip relationship, and the critical bond stress are obtained from the data of the GFRP grouting anchor in domestic and foreign countries (Zhao and Yuan, 2016).

2. Properties and characteristics of GFRP synthetic materials in experiment

A synthetic material can be defined as the composite synthesized of two or more different materials that can be seen by the naked eye and it can distinguish from the interface. The FRP synthetic material is essentially synthesized by dipping fibre into resin matrix. Filament fibres contain a variety of high tensile strength and high

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elastic modulus fibres. The most commonly used fibres are aramid fibre reinforced plastic (AFRP), carbon fibre-reinforced plastics (CFRP), glass-fibre-reinforced plastic (GFRP). The matrix is used as a bonding material to keep the fibres together. In order to allow the transfer of load and to prevent the shear force between different fibres, it is necessary to protect the fibre and maintain the stability of the fibre. Most of the base material used are a mixture, epoxy resin and ethylene. The GFRP synthetic material used in the reference test is the production of glass fibre filled in a thermoset resin. The properties of the materials used are as follows (Yang et al., 2016)

(1) Glass fibre

The glass fibre is the most common of all FRP reinforced fibres. Its production is to make the melt glass into a shape through a hole. Its main advantages are low price, high tensile strength and good electrical insulation. The two most common types of glass fibre are E-glass fibre and S-glass fibre. E-glass fibre is a kind of cheapest fibre in all the common seen and economic reinforced fibres. It is often used in the conditions with reinforcement, anti-electricity, anti-acid environment and low cost. S-glass fibre has higher strength, toughness and ultimate strain, but it is more expensive. And when used in alkaline environment, it can be lower than the grade of E- glass fibre. Other types of glass fibres are C-glass and alkali resistant (AR) glass fibres. C-glass fibre has good chemical stability in alkaline environment, and the weight of AR- glass fibre is very small so that it can reduce the loss in alkaline environment. The physical and chemical properties of various glass fibres are given in table 1.

Table 1: The physical and chemical properties of various glass fibres

Parameters	E- glass fibers	S- glass fibers	C- glass fibers	AR- glass fibers
Tensile strength (GA)	3.45	4.3	3.03	2.5
Tensile modulus (GPa)	72.4	86.9	69.0	70.0
Ultimate strain (%)	4.8	5.0	4.8	3.6
Poisson ratio	0.2	0.22	-	-
Density (g/cm^3)	2.54	2.49	2.49	2.78
Diameter (pm)	10.0	10.0	4.5	-
Longitudinal expansion coefficient (10-6/°C)	5.0	2.9	7.2	-
Insulator constant	6.3	5.1	7.2	-

(2) Multi-vinegar resin

Thermosetting resins usually contain unsaturated vinegar polymers that are dissolved in many monomers, such as styrene. Depending on the composition of the mixture, the characteristics of the multi-vinegar resin vary greatly. The multi-vinegar resin has the characteristics of fire resistance, damp resistance, acid and alkali resistance, but its performance will be reduced in the chloride solvent. The highest service temperature of the multi-vinegar resin is 120 DEG C, which is used for FRP steel, and its main advantages are low viscosity, short solidification time, good dimensional stability, good chemical resistance and low price. The main disadvantage of unsaturated multi-vinegar is the high volume shrinkage in the production process. However, their low synthesis cost, easy for processing, good plasticity and other advantages make them widely used in the production of FRP bar in the resin. Table 2 shows the physical and chemical properties of multi-vinegar.

Table 2: The physical and chemical properties of multi-vinegar

Parameters	Multi-vinegar resin
Tensile strength (MPa)	20-100
Tensile modulus (GPa)	2.1-4.1
Ultimate strain (%)	1-6
Density (g/cm3)	1.0-1.45
Temperature expansion coefficient (10-6/°C)	55-100
Shrinkage (%)	5-12

(3) Types and characteristics of GFRP bars used

The three types of GFRP bars used in the experiment were: GFRP A, B and C. Select the nominal diameter of 25mm bars used in the test, and used the steel with the same diameter and steel strand after post tensioning in the test for the comparison. GFRP A, in the production process, used the same type of fibre tension and pressure to get the groove on the surface. GFRP B type of steel contains a small amount of fibre in the form of spiral winding on the longitudinal fibre. The role of the winding fibre is to get the reinforcement on the irregular

surface, and the pitch and groove of GFRP B type of bars are larger than those of the GFRP A type. The GFRP C type is smooth on the surface, and the fibre on the surface is loose.
Table 3 shows the mechanical properties of GFRP tendons and steel tendons. It can be seen that the tensile strength and modulus elasticity of GFRP A, B and C are 958Mpa and 50GPa, 690Mpa and 45GPa, 595Mpa and 39GPa, respectively. The tensile strength of GFRP tendons is 1.5-2.4 times that of ordinary steel tendons and 0.7-1.1 times of steel strand. The elastic modulus of GFRP tendons is 20-25% of the steel tendons. The ultimate loads that GFRP A, B and C correspond to are 470KN, 339KN, and 292KN. The elastic limit and ultimate load of ordinary steel tendon and steel strand with diameter of 25mm are 196KN and 295KN, and 417KN and 515KN, respectively.

Table 3: Mechanical properties of GFRP tendons and steel tendons

Parameters	GFRP A	GFRP B	GFRP C	Steel tendons	Steel strand
Tensile strength (MPa)	958	690	595	400	850
Elastic modulus (GPa)	50	45	39	200	200
Density (g/cm3)	2.0	2.0	1.9	7.8	7.8

3. Two kinds of pull-out tests

(1) Laboratory pull-out test
The 600mm * 600mm * 400mm concrete block is used as the medium to install the anchor rod, the compressive strength and the elastic modulus of concrete are 83MPa and 38GPa, respectively, and four bolts are installed on each concrete. Using resin cylinder as model casting in concrete blocks in 50.8rnrn diameter drilling hole, to get the drilling convex surface getting closer to the reality. In this way, it can prevent the interface failure of bolt in concrete and mortar. The resin column is pulled out within two days after pouring. Only the GFRP C type anchor has the bond length of 127mm (5dB), the remaining anchors choose two bond lengths: 63.5mm (2.5dB) and 127mm (5dB), and db is the diameter of the GFRP anchor. In the top, the bond length greater than 150mm, use PVC pipe to isolate the mortar and anchor, so as to eliminate the effect of supporting force acted on the anchor. The space between the anchor elements in each concrete block is maintained at a minimum of 180mm, so as to avoid the interaction between adjacent anchors (stress overlap, crack propagation and so on). Four types of GFRP bolt pull-out tests were carried out 14 days after the bolt grouting.
All the bolts are injected in concrete blocks with ordinary cement. The cement grade is 525, water cement ratio is (W/C), 0.4, the mortar strength in the test reaches 52MPa, and the elastic modulus is 17GPa. The pull-out test of the anchor rod is carried out with a hollow 300KN hydraulic jack. The sliding of pull-out load and the loading end were recorded by data electronic automatic recording instrument. The loading speed was fixed at 5KN/S.
(2) Field pull-out test
The performance of GFRP bolt in field installation conditions was determined by field pull-out test. All the bolts are installed in the same place, and the rock is a kind of hard sandstone with two kinds of textures randomly combined. The quality of rock mass around the installation area is evaluated according to the RMR method (RMR=75) and the NGI method (Q=16~18), which is assessed excellent. The deformation modulus in the original position can be estimated by the RMR methods as follows: EM=2RMR-100(GPa). As a result, in this case, EM≈50GPa. The estimated value of EM is close to the elastic modulus of rock samples (61±3GPa). With spiral drill, we can drill the holes with the vertical of 76.2mm, and then we use the cement slurry similar to that used in the laboratory to bond the anchor bond in the cave. In the field test, two kinds of anchorage length were 150mm and 450mm, respectively, including GFRP anchor and steel strand bolt. At the top, the bond length above 150mm, we can use PVC casing to isolate the anchor and mortar. Each of the two bond lengths was tested 14 days after grouting.
In the anchor pull-out test in the field, what used in the loading is similar to that used in the loading of anchors in concrete blocks. The sliding of pull-out load and the loading end are monitored by the using the pressure measuring element and the displacement meter, respectively. The load increases gradually until it breaks down.

4. Results and discussion

4.1 Carrying capacity

The average maximum carrying capacity of anchors installed in concrete blocks and in rocks is shown in Figures 1, respectively. The test results (Figure 1) said that, as the bond length increases, the bearing capacity increases linearly. It can also be seen that the steel anchor bolt has the highest average carrying capacity (corresponding to 63.5mm and 127mm for bolt anchorage length were 62KN and 138KN). The average load capacity of GFRP C bolt is the lowest, and the average bearing capacity of anchor with the bond length of 127mm is 29KN. The average load carrying capacity of GFRP A and GFRP B is 49KN and 117KN, 57KN and 128KN, respectively, with the bond length of 63.5mm and 127mm. This is the same as the level of the steel strand anchor (the bond length of 63.5mm is 43KN, and the bond length of 127mm is 129KN).

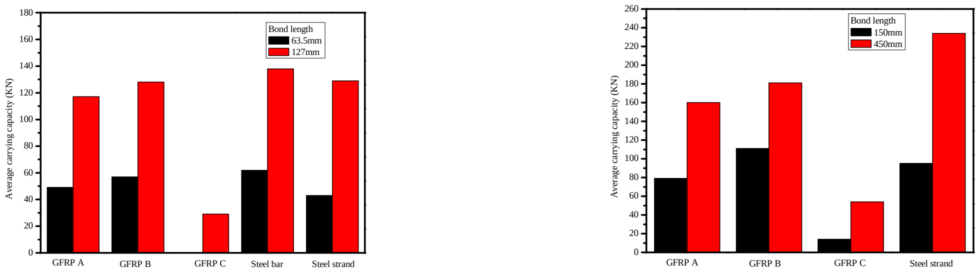

Figure 1: Average carrying capacity of anchors installed in concrete blocks and Average carrying capacity of anchors installed in rock blocks

The pull-out test results in the field are similar to those of the anchors installed in concrete blocks (Figure 2). The bearing capacity increases linearly with the increase of the bond length. When the bond length is 150mm, the average carrying capacity of GFRP A and B bolt is 79KN and 111KN, respectively, which is close to the bearing capacity of steel strand bolt. The bearing capacity of the GFRP C bolt is the lowest, and the bearing capacity of the anchor rod corresponding to the length of 150mm and 450mm is 14KN and 54KN, respectively. As expected, the premature failure of the GFRP A and the B bolt with the bond length of 450mm is caused by the anchoring clamping force, and the shear failure occurs at the interface between the anchor and cement paste. When loading, due to the damage caused by the tensile strength of the tendon, the GFRP A and GFRP B anchors accounted for 36% and 55%, respectively. The damage is basically under the anchor and the anchor is split. Because the FRP reinforcement is quite sensitive to the multiaxial stress, and lateral shear strength and compressive strength are low, lateral shear failure and compression failure are the main reason for low load failure. It indicated that it is necessary to develop the anchoring device more suitable for FRP anchor.

4.2 Cohesion strength

The results of Table 4 and 5 showed that the average shear bond strength of profiled FRP A and B bolt is greater than that of smooth GFRP C anchor. This can use heterotypic (or linear) GFRP bond strength, which is basically by the mechanical bite force to fully mobilize the sheer force of the cement cylinder (the reinforcement of the groove to bear the reaction of cement paste) to explain. On the other hand, the bond strength of anchor with sand and smooth surface bolt mainly formed by a friction shear resistance force of bolt mortar interface. GFRP B anchor has large deformation due to the damage and damaged by mortar interface shear bolt. GFRP A anchor deformation is relatively small, so the destruction of GFRP A anchor is due in part to crush of a bolt and mortar interface shear. As a result, the bond strength of GFRP A is lower than that of GFRP B. The damage of GFRP C bolt is due to the surface fibre delamination and because the fibre is cut loosely.

Table 4: Average bond strength and slip of anchor bolt in concrete block in the anchor damage

Types of anchor	The bond length of 63.5mm		The bond length of 127mm	
	The bond strength (MPa)	Failure slip (mm)	The bond strength (MPa)	Failure slip (mm)
GFRP A	9.5	1.58	11.8	1.59
GFRP B	11.4	2.49	12.7	4.92
GFRP C	-	-	2.5	9.08
Steel tendons	12.7	1.63	13.8	0.78
Steel strand	8.7	0.78	13.4	0.52

Table 5: Average bond strength and slip of anchor bolt in rock block in the anchor damage

Types of anchor	The bond length of 150mm		The bond length of 450mm	
	The bond strength (MPa)	Failure slip (mm)	The bond strength (MPa)	Failure slip (mm)
GFRP A	6.4	2.42	4.8	-
GFRP B-1	9.6	2.86	5.4	-
GFRP C	1.4	6.43	1.6	8.29
Steel strand	6.2	3.24	6.4	4.20

From Table 4 and 5, it is known that, the laboratory tests showed that the bond strength is higher than that of the field test. This is because the radial stiffness at each main anchor in a medium mortar interface is different. The research showed that the radial stiffness has a great influence on the bond strength. In a radial anchor-mortar interface, the stiffness is affected by mechanical and elastic properties of mortar, the main medium, geometry and drilling rod. Radial stiffness ratio of main medium in the field test is lower than that in the laboratory. This is because the thickness of the bonding mortar increases (the diameter of hole in the field test is 76.2mm, and that in the laboratory is 50.8mm). As a result, the bond strength in the field test is lower than that in the laboratory.

4.3 Load-slip performance

Because the elastic modulus of the GFRP tendon is about 25% of the reinforcement, the elastic elongation of the GFRP anchor is four times that of the steel tendon at the top of the bond length and the measuring point of the tendon. When the elastic elongation of GFRP tendons is taken into account, the slip along the bond length can be expressed as:

$$\delta_{slip} = \delta_{total} - \delta_{bar} \quad (1)$$

In (1), δ_{slip} refers to the longitudinal slip along with the bond length GFRP anchor; δ_{total} indicates the longitudinal slip measured;
δ_{bar}represents elastic elongation of GFRP bars.

$$\delta_{bar} = (PS)/(AE) \quad (2)$$

In the formula, P is the load; A is the cross-sectional area; E is the elastic modulus; S is the distance from the top of the bond length to the LVDT (micrometre) measurement points or micrometre.

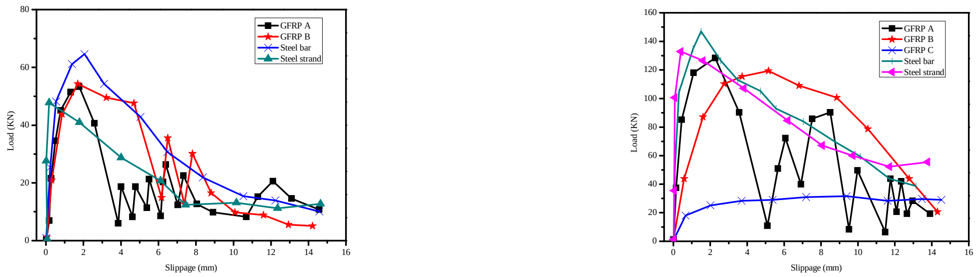

Figure 2: Pull-out test load - slip performance of GFRP anchor rod and steel anchor rod in anchor length of 63.5mm concrete block and Pull-out test load - slip performance of GFRP anchor rod and steel anchor rod in anchor length of 127mm concrete block

The relationship between the end slip of the GFRP anchor and the anchor rod and the corresponding applied load in the concrete block or rock block is shown in Figure 2 to Figure 3. Basically, the load - slip behaviour of GFRP A and B anchors is similar to that of steel anchors. The load - slip curves include the rising and the falling. In the rising part, a given slip added load of the corresponding bolt head will be significantly increased, until it reaches the peak load; the load transfers from the anchor to the slurry, mainly by the function of bonding and mechanical interlocking. For anchor shaped surface, the latter one contributes a lot to the total load; the GFRP B anchor has a larger slip before reaching the peak load. In the falling part, for a given slip added value load decreasing sharply, residual load depends not only on the friction resistance, but also relies on the mechanical bite force between the mortar and rock bolt, load fluctuation as shown in Figure 2 to Figure 6. Because of its smooth surface, GFRP C anchor has different load - slip behaviour. Before the bolt and the mortar loosened, the bearing capacity is mainly dependent on the bond between bolt and mortar; and after loosening, it depends on the friction.

Figure 3: Pull-out test load - slip performance of GFRP anchor rod and steel anchor bolt in anchor length of 150mm rock and Pull-out test load - slip performance of GFRP anchor rod and steel anchor bolt in anchor length of 450mm rock

5. Conclusion

The main purpose of studying the anchoring mechanism and anchoring performance of fiber polymer anchor rod is to apply it in practical engineering. This requires our research work is supposed to be based on lots of specific tests and value simulation. In this paper, the main conclusions are as follows: FRP anchor is installed in concrete block and field rock, and the bond properties and the bond strength are basically similar. With the increase of anchorage length, the cohesive force increases linearly, and the distribution of bond stress along the anchorage length can be divided into rising and falling. In the anchor test, the sliding of FRP bolt in damage is greater than that of steel anchor, which is due to the small elastic modulus of FRP anchor bolt and the smooth surface of FRP anchor, and that is also the reason for the large slip in concrete.

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