Discussion on the Research of GFRP Anti-floating Anchors

Yingqian Cao¹, *

¹North China University of Technology, Beijing 100043, China;
*Guanghua.ren@genacademy.cn

Abstract: As a kind of anchor to deal with the anti-flotation problem of floor, anti-flotation anchors have many advantages, such as strong adaptability to stratum, high anchoring force, low cost, short construction period, small stress at single point, simple construction and low cost, compared with the traditional anchor. In recent years, it has been more and more applied to solve the problems of foundation pit supporting and foundation floor anti-floating in the construction process of buildings. In this paper, the stress and strain distribution law, load transfer characteristics and the relationship between GFRP anti-floating anchor and rock mass of GFRP anti-floating anchor are summarized, and suggestions for the future development of GFRP anti-floating anchor are put forward.

1. Introduction

In recent years, the urban underground water level is rising due to the continuous expansion of urban space and foundation burial depth. It is common that the structural load cannot resist the buoyancy of groundwater. Anti-floating anchor bolts are widely used in the engineering of anti-floating problems of foundation floor of building [1] because of its advantages of small stress at a single point, simple construction technology and low cost [1-4]. Glass Fiber Reinforced Polymer bolt is a new type of fiber reinforced bolt made of glass fiber and synthetic resin by pultrusion and curing. Glass fiber reinforced polymer with metal anchor bolt, compared with high tensile strength, good corrosion resistance [2] and dielectric properties and advantages such as low cost can be used in the optical fiber monitoring [3]. In the past hundred years, anti-floating bolt technology has developed rapidly. In 1960s, the development of Glass Fiber Reinforced Polymer bolt has made great progress in foreign countries [4]. The study of GFRP bolt in China started later than that abroad. In 30 years, many scholars also successfully proved the feasibility of GFRP bolt in replacing reinforced bolt in rock engineering [5]. In this paper, the distribution law of stress and strain is introduced in section1. The Load transfer characteristics of GFRP bolt are reviewed in section2, and the relationship between GFRP anchor bolt and rock body is discussed in section3. Prospects for future researches are listed in section4. Section5 concludes the findings of this paper.

2. The distribution law of stress and strain

2.1. The stress-strain relationship of ultimate bearing capacity of anchor bolt

Bai et al. [6] found in the study of 13 rock anti-floating bolts in 4 groups loaded to the ultimate failure state and the installation of a fiber grating strain sensor on one of the test tank rods that at the initial stage of loading, with the increase of the drawing load, the displacement of the top surface of the anchor solid continues to increase and gradually enters the plastic deformation stage, and the change rate of the displacement of the top surface of the anchor solid increases gradually. Under the same material,
diameter and solid strength of anchor bars, the ultimate tensile strength of anti-floating anchor increases with the increase of bond length. However, there is no direct correlation between bond length and ultimate pull-out capacity.

Luo etc. [7] based on nine different diameters of GFRP bolt tensile test and 27 different diameters and surface morphology of GFRP bolt bonding performance test found, GFRP bolt groups of specimens in the process of the normal basis for linear elastic materials. Although the diameter is different, the stress-strain curve slope basic same, elastic modulus changed little, stress-strain curve for a diagonal line through the origin. For the ultimate tensile strength of different diameters, with the increase of specimen diameter, although the ultimate tensile strength decreases, the ultimate load increases.

2.2. Stress-strain relationship of axial stress
When Long et al. [8] derived the simplified formula for critical anchorage length of anchor bolt, they believed that the displacement curves of the anchor bolt and uplift pile under load went through stages of elastic deformation, elastoplastic deformation, and failure, and the displacement curves were basically consistent in morphology.

Bai et al. [6] designed a experiment of loading 13 rock anti-floating bolts in 4 groups to the ultimate failure state and installing a fiber Bragg grating strain sensor on one of the test bolts. In the experiment he found that with the increase of load level, the axial force transmission depth of the anchor bars proportionally increases along the depth. Moreover the anchorage depth is inversely proportional to the decay rate of the axial force of the anchor bar. When the bond length of anchor bars reaches a certain value, the ultimate pull-out capacity of anti-floating anchor bolts cannot be improved only by increasing the bond length.

Bai et al. [9] found in the Qingdao phase 1 subway (line 3) Ningxia road no. 3 B entrances and exits of 6 GFRP reinforced feasibility of the feasibility and 4 at the scene of full-scale drawing destructive test. When the load is small, the load-anchor head displacement curve is linear. When the load is large, the load-anchor head displacement curve becomes nonlinear.

When Bai et al. [10] studied the indoor full-scale pull-out destructive tests of four rock GFRP anti-floating anchors, they found that the relationship curve between the drawing force and the tension deformation of the anchor head becomes nonlinear with the increase of the load level. The increase of anchor length of GFRP bolt also increases the load-bearing capacity and slippage of the bolt.

Liu et al. [11] in combination with Beijing new poly plaza project discussed dispersed pressure feasibility test found, for pressure type feasibility unit in different soil layer anchor rod drawing force and tension anchor head deformation basic linear relationship, one unit and bolt pulling force is insufficient, will directly affect the whole bolt pulling force. The relationship curve between unit anchor bolt pulling force $Q$ and anchor head tension deformation $S$ is shown in Figure1:

![Figure 1](image_url)

Figure 1 The relation between pull-out force of unit bolt and tension deformation of anchor head

Xiao [3] found in the vertical pull-out static load test of 16 anti-floating anchor bolts tested that the vertical pull-out ultimate bearing of anti-floating bolts in the project under the same parameters can reach 1.5 times the designed value of axial tension. The load-displacement curve shows that with the
gradual increase of the vertical pulling force of anti-floating anchor, the vertical displacement of some bolts changes from slow to fast, and a certain plastic deformation appears.

When Ma [12] studied the displacement and internal force of a tension-type anti-floating anchor bolt in a basement he found that, the displacement of anchor head changed uniformly in the loading process, and the displacement generated by the second stage load was all less than 2 times of that generated by the previous stage load. When the load reaches the maximum tensile load, the anchor head displacement of the anti-floating anchor bolt is stable at a certain value.

Zhao et al. [13] through the reinforced feasibility of field destructive test and comparison of the results of numerical simulation software of ABAQUS found that when the load is less than 230kN, the distribution of bolt pulling force and anchor head tensile deformation is a straight line (elastic deformation stage). With the increase of load, the distribution of the two is roughly curved (accelerated slip, and cracks appear between bolt and mortar interface), and the bolt shows pull-out failure.

Huang et al. [14] found that under three surrounding rock conditions of fully weathered, strongly weathered and weakly differentiated, the strain of the bolt is positively proportional to the change of load in the experiment of the bolt sticking strain gage with the whole length and cyclic loading. Strain attenuation of the rod near the shallow orifice is faster. With the increase of depth, the strain attenuation amplitude of the rod decreases to a lower level gradually. Under the same surrounding rock and the same load conditions, the bolt's stress attenuation process and transmission depth are close to each other. The anchoring length has a great influence on the bearing capacity of the bolt. With the same surrounding rock conditions, the bearing capacity and strain transfer depth of the same batch of bolts differ greatly.

When the bolt length is certain, there will be a critical value of the length of the anchor section under a certain pulling force, and the tangential displacement of the bolt body will increase if the length exceeds this length. The length of the anchorage section should not be too short.

When Liu et al. [15] studied the stress-strain relationship of the GFRP bolt with the help of a tensile test, they found that when the load value is not less than 80% PU, the strain increment increases significantly, but it does not fail. With the increase of load, the specimen fails. Moreover, the stress-strain curve of GFRP bolt has no obvious yield point, and the whole test process is basically elastic deformation, and the failure of the specimen is a brittle failure.

Ren et al. [16] consideration in the interface friction effect after the destruction of the Cohesive unit to simulate the interface between the composite bolt fracture damage found that when the load is less than 100kN in the linear elastic deformation stage, along with the load increase, entered the stage of softening, yield surface of a bolt, will eventually happen interface slip and further damage.

Zhang et al. [17] In the field drawing test, the load and slip of different types of reinforced anti-floating anchors are all in a positive ratio relationship to the field drawing test. At the initial stage, the change of slip with load is not obvious. After loading to 240kN, the variation of slip increases linearly until the failure of the bolt, and finally, the slip of each bolt is about 20mm.

Bai et al. [18] found in the field pull-out destructive test of three full-thread GFRP anti-floating bolts that when the load is small, the relationship between the load and the displacement is linear. With the increase of the load, the anchor head’s pulling rate increases gradually, and the load-displacement curve becomes nonlinear.

Li [19] conducted two field tests at the east entrance of Ningxia Road Station of Qingdao Metro Line 3 to compare the data of two materials. The displacement of the GFRP bolt increases slowly with the increase of load. Under the same level of load, the displacement of the GFRP anchor head is greater than that of the reinforced anchor head.

When Wu et al. [20] compared and analyzed the characteristics of a pressure-type bolt and tension-type bolt by means of theoretical analysis and field test, they found that under the same load, the displacement increment of pressure-type bolt is more uniform at each stage of load, and the displacement of the anchor section is far less than that of a tension-type bolt. The deformation of anchor mortar of pressure type bolt is much smaller than that of tension-type bolt under the same condition.

Kuang et al. [21] concluded through theoretical derivation and field drawing test combined with finite element analysis software ANSYS modeling analysis. When the load of the GFRP bolt is small,
the bond stress changes in a linear proportion to the change of load. When the load is large, the bond stress decreases with the increase of load.

Through the in-situ drawing test designed by Zhu et al. [22] and the combination of actual engineering, there is no obvious inflection point in the curve of the GFRP anti-floating anchor bolt, showing a slow decline trend.

Bai et al. [23] found in the field test of GFRP anti-floating bolt and its bonding performance using an inverted concrete floor that the shorter the bending length of GFRP bolt, the more gentle the load-slip curve the greater the uplift bearing capacity of the bolt; For the GFRP bolt without bending treatment, the slip between the GFRP bolt and the concrete floor decreases with the increase of the diameter of the bolt under the same vertical anchoring length. At the same bending length, the pull-out bearing capacity of the GFRP bolt is proportional to the change of vertical anchoring length. Under the same load grade condition, the GFRP bolt body and concrete floor slip are inversely proportional to the change of vertical anchorage length. The slip of bolt and concrete increases linearly with the increase of load level.

Bai et al. [24] through nonlinear finite element software ABAQUS, the Cohesive bond unit simulation when contact with the interface between the rod body found that when the load is not higher than 150kN, GFRP bolt elastic deformation, displacement increases with the increase of the load and constant. When the load is not high, more than 100kN, load and displacement of a linear change.

2.3. Stress-strain relationship of shear stress

When Bai et al. [25] analyzed the deformation composition of GFRP anti-floating anchor bolt from the perspective of total deformation they found that when the top surface displacement of the anchor solid was small, the shear stress reached the peak at the top surface of the anchor solid at the beginning, and then gradually decreased along the depth direction of the anchor solid, and finally approached zero. The distribution pattern was basically inverted triangle. The shear strain of anti-floating anchor is deduced as follows:

The shear strain of anti-floating anchor

\[
\gamma = \frac{\partial u}{\partial x} + \frac{\partial \omega}{\partial r}
\]

Where: \(\mu\) is the transverse (R-direction) strain of the rock and soil mass, and \(\omega\) is the vertical (X-direction) strain.

Chen et al. [26] deduced the stress and strain relationship of anti-floating anchor bolt by applying mechanics principle, and found in the study of anti-floating anchor bolt in Shenzhen Diving Natatorium as the basic test, the deformation of the anchor solid is smaller than the shear deformation of anchor interface and the deformation of soil. The deformation of the anchor solid which mainly concentrated at the end has little relation with the drawing force. The deformation at the interface of the anchor soil varies uniformly, while the soil deformation transfers to the bottom faster with the increase of the load. The deformation of the end body is not obvious, and the changing trend of the end body is consistent with the lateral friction resistance. With the increase of load, the growth range of interface shear deformation and body deformation is gradually greater than that of anchor solid deformation.

2.4. Stress-strain relationship of long-term load

Bai et al. [27] found through the step-by-step increasing load test of 4 GFRP anti-floating bolts with a diameter of 25mm that the creep rate of GFRP anchor bolts decreased gradually in the initial stage and the deformation was stable after the creep rate rapidly decreased to 0. By introducing Burger mechanics model and damage mechanics theory, the variation rule of damage variable with time and the long-term pull-out strength of GFRP anti-floating anchor bolt were deduced:

Changes of damage variables of GFRP anti-floating anchors with time

\[
\omega(t) = 1 - \frac{P(t)}{P(0)}
\]

Where, \(\omega(t)\) is the damage variable of GFRP anchor bolt, \(P(t)\) is the deformation stiffness of GFRP anchor bolt at time \(t\), and \(P(0)\) is the deformation stiffness of GERP anchor bolt at time 0.

Long-term pull-out strength of GFRP bolt
\[ F_\infty = (1 - \omega_\infty)F_0 \]  

(3)

Where, \( F_\infty \) is the long-term pull-out resistance of GFRP anti-floating anchor bolt, and \( F_0 \) is the ultimate pull-out bearing capacity of GFRP anti-floating anchor bolt.

2.5. Influence of bending treatment on strain

Based on the field full-scale pull-out destructive tests of 8 surface viscous sand GFRP composite anti-floating bolts and 8 thread reinforced anti-floating bolts, Kuang et al. [2] found that, for GFRP composite anti-floating bolts, although bending treatment can effectively reduce the slip of the bolt, the bending length is proportional to the effect of displacement restriction.

Zhang et al. [17] found in the field pull-out test that all the reinforced anti-floating anchors treated by bending occurred pull-out failure, and the failure location was all 7cm-9cm away from the concrete surface. For bolts with different bending lengths, the smaller the bending length, the greater the slip. Under the same load, the slip amount of two bolts with equal anchorage length is basically equal.

3. Load transfer characteristics of GFRP bolt

3.1. Load transfer characteristics of axial stress

Su et al. [28] through by 6 on the spot of the anti-floating anchor rod under continuous load destructive pull-out test found that when the load is less than 270kN, bolt axial force is proportional to the load change; When the load is larger than 270kN, the increasing rate of axial force is bigger and bigger and the anchor tension when the axial force gradually moves down with the load.

Chen et al. [26] deduced the stress-strain relationship of the anti-floating anchor by applying mechanics principle, and found in the study of the anti-floating anchor in Shenzhen Diving Natatorium as the basic test that both the axial force and the lateral friction resistance are proportional to the change of the pulling force of the anchor.

Zhao et al. [13] through the scene of the reinforced feasibility of destructive test combined with numerical simulation software ABAQUS study found that when the load is small, the axial stress distribution transfer direction is downward. When the load is large, the distribution range of the axial force will increase.

When Ma [12] studied the displacement and internal force of a basement tension-type anti-floating anchor bolt, he found that when stretching by grade load, the grade load reaches the ultimate load, the stress of each part of the anchor bolt also reaches the maximum; The deeper the depth is, the smaller the axial force of each part of the bolt is, and the axial force of the bolt is almost zero. The axial stress is concentrated at the end of the anchorage section, and the end will be damaged first when the load increases to a certain value.

Zhang et al. [29] found in the pullout test study of anti-floating anchor in Qingdao Grand Theatre Project that a load of anchor varies from large to small from the ground to the bottom of the anchor, and most of the axial force is distributed within 2m below the ground.

When conducting numerical simulation through ABAQUS, Jia [30] found that, when the load is small, the interface is not decoupled, the axial force along the axial length of the bolt presents a negative exponential distribution, and there is axial stress at the far end, and the load is proportional to the change of axial stress; When the load increases to a certain extent, the range of axial stress increases and the interface begins to decouple.

Bai et al. [18] found that when the increase of load in the deep part was large, the increase of load in the shallow part was small. Under the condition of moderately weathered granite, the reasonable anchoring length of 28mm GFRP anti-floating rock bolt should be 3.5m ~ 6.0m.

Li [19] found that the axial force distribution length of the GFRP bolt and reinforced bolt is basically the same when comparing and analyzing the bearing characteristics of the two materials based on the data of two field tests at the east exit and entrance of Ningxia Road Station of Qingdao Metro Line 3. Most of the axial force of the bolt body is located at a depth of 0-2m, and near the depth of 2.1m, the axial force of the bolt body has decayed to about 10% of the axial force of the loading end.
Considering the multi-interface contact, Bai et al. [31] used ABAQUS numerical simulation software to establish the axisymmetrical numerical calculation model of the GFRP anti-floating anchor system with the influence of foundation floor deformation and found that when the load level was 200kN, the axial stress reached the maximum. When the water head is 5.0m above the foundation floor, the axial stress of the anchor bars in the anti-floating bolt system peaks at the interface between the stratum and the foundation floor. When the water head is 10.0m above the foundation floor, stress concentration occurs at the interface of the foundation floor, and the distribution range of axial stress in the inner and outer anchorage sections is 0.3-2.2m. When the Waterhead is 5.0m above the foundation floor, the peak value of axial stress increases by 1 time. The attenuation rate of anchor bars along the depth in the foundation plate is faster than that in the formation.

Kuang et al. [21] concluded through theoretical derivation, on-site drawing test and finite element analysis software ANSYS modeling analysis that the axial force of GFRP bolt maximizes at the port, and gradually decreases along the length of the bolt from the port, and decreases to 0 within a small length range. The load is proportional to the change of port axial force of the anchor bolt, and the influence range of the anchor increases insignificantly with the increase of load.

By using the nonlinear finite element software ABAQUS, Bai et al. [24] simulated the contact between rod and interfaced with Cohesive element. They found that when the load is low, the axial stress is inversely proportional to the change of anchorage depth; when the load is no more than 150kN, the axial force decreases to 0Pa along the anchorage depth, which is approximately in the form of negative exponential distribution; When the load is no more than 200kN, the axial stress is in the form of negative exponential distribution. With the gradual increase of load, the axial force in a certain range below the orientation increases sharply.

According to the comprehensive analysis of the test results of the bond performance between fiber polymer bars and concrete, Gao [32] found that the tensile stress decreased rapidly from the loading end to the free end along the buried length of glass fiber polymer bars and the distribution of reinforced concrete. As the bond failure progresses gradually, the corresponding bond stress limit value is closer to the free end. The nonlinear distribution of bond stress between glass fiber polymer bars shows that the average bond strength decreases with the increase of buried length at a given diameter.

3.2. Load transfer characteristics of shear stress

Bai et al. [6] found in the experiment of loading 13 anti-floating rock bolts in 4 groups to the ultimate failure state and installing an FBG strain sensor on one of the test bolts that the shear stress of the anchor bar increases first and then decreases along with the depth and is near the top surface of the anchor solid, and the value of the shear stress is large and the distribution is concentrated.

Su et al. [28] found in the test of the destructive pulling resistance of 6 anti-floating bolts under continuous load that with the increase of load, the distribution of shear stress gradually moved downward.

When Jia [33] conducted destructive experiments on anti-floating anchor bolts used in an underground project in Dalian, he found that shear stress between grouting body and rock mass under an external load of anchor bolts reached the maximum near the Orient and attenuated along the length of anchor bolts. When the external load reaches the ultimate state, the ultimate shear stress tends to be stable and develops to depth. At this time, the shear stress changes slowly along the length of the bolt, but the distribution of shear stress is not uniform.

Zhang et al. [29] found in the pullout test study of anti-floating anchor in Qingdao Grand Theatre Project that, under different loads, the shear stress between the bolt body and the grouting body of the three bolts distributed unevenly along the rod body and gradually decreased from top to bottom.

In ABAQUS numerical simulation, Jia [30] found, when the load level is low, the increase of load series is proportional to the interface shear stress, and the distal end of the load decreases continuously, but the distal end of the shear stress is not 0; When the load reaches a certain level, relative slip occurs at the near end of the load, and the peak shear stress keeps moving to the far end. As the load continues
to increase, the shear stress on the proximal side decreases, and the peak value of the shear stress continues to increase and move to the distal end until the specimen is damaged.

Huang et al. [14] found in the test of the bolt sticking strain gage with the whole length of the bolt and cyclic loading on the bolt that the change of load is proportional to the change of the peak value of the shear stress curve. When the peak value of shear stress reaches 20MPa between the GFRP bolt and the bond mortar, shear failure occurs at the interface between the bolt and the bond mortar. As the load increases and moves to the depth, the influence range of shear stress also increases.

When Ren et al. [16] simulated the interfacial fracture failure of composite bolt materials using a Cohesive element considering the friction after interfacial failure, they found that the shear stress development distribution of cement mort-body interface showed a positive exponential distribution. The anchorage mechanism of the composite bolt is greatly affected by the shear stress of the main control surface, and the distribution law of the stress of the main control surface is roughly the same as that of the common reinforced bolt. In addition, the other interfaces except the main control surface are not softened, and only the corresponding coordinated deformation and adjustment are carried out with the softening damage of the main control surface.

Bai et al. [18] Based on the three full thread GFRP at the scene of the anti-floating anchor rod drawing destructive testing found, the shear stress on the interface between the GFRP anti-floating anchor body and the anchor solid changed from zero to the maximum value at the hole mouth, and gradually decreased to near zero at the end of the anchor solid.

Li [19] in Qingdao metro line 3 road station east Ningxia twice at the entrance of the field test data for two kinds of material of anchor the load-bearing characteristics of comparative analysis and research found the difference between the material of GFRP and steel bar. Under the action of external tension, the stress of the bolt gradually develops from shallow to deep, and the deformation of the GFRP bolt is large. When the load is large, the contact place between the shallow mortar and the bolt body slips, and the stress develops to the depth of the bolt.

Considering the multi-interface contact, Bai et al. [31] used ABAQUS numerical simulation software to establish the axisymmetrical numerical calculation model of GFRP anti-floating anchor system with the influence of foundation floor deformation and found that when the simulation result of the load level of 200kN was 63.7kPa, System of GFRP anti-floating anchor rod anchor bar shear stress there are two peaks of bonding of the foundation slab and the formation to be ignored, the system of anchor bar outside the shear stress distribution and the outer anchorage segment of anchor bar within the peak shear stress more than 5 times of anchoring section of the peak shear stress.

Kuang et al. [21] through the field drawing test and finite element analysis software ANSYS modeling analysis concluded that the shear stress of GFRP anchor bolt reached the maximum near the port through theoretical derivation and it decreased sharply along the length of the anchor bolt, and the influence range of anchor was small. The drawing force is proportional to the peak shear stress. The diameter of bolt is inversely proportional to the peak shear stress. The distribution range of shear stress increases with the increase of bolt diameter.

Bai et al. [24] through nonlinear finite element software ABAQUS, the Cohesive bond unit simulation when in contact with the interface between the rod body found, when the load of 50kN, rod body and the maximum shear stress in the orifice of cement mortar, with the increase of the load, the shear stress peaks along with the anchoring depth gradually shift.

4. Relationship between GFRP anchor bolt and rock body

4.1. Stress

Bai et al. [24] through nonlinear finite element software ABAQUS and the Cohesive bond unit simulation and the interface between the rod body found, when in contact stress of the surrounding rock increase with the increase of the load, and pass down the anchoring depth gradually, the GFRP feasibility of surrounding rock mass and grouting body horizontal scope with the increase of load increases accordingly. Moreover, the vertical displacement of surrounding rock mass is almost not caused by the
applied load on the anchor, and the maximum vertical stress of surrounding rock mass occurs at 1/15 of
the anchorage depth of the anchor bolt.

Cui et al. [5] found that through indoor pull-out tests of GFRPP bolts and cement mortar with
different anchoring depths, the load time curve of the sample showed irregular changes in the initial
stage of loading.

Bai et al. [9] through the Qingdao phase 1 subway (line 3) in Ningxia road No. 3 B entrance 6 GFRP
reinforced feasibility of the feasibility and 4 at the scene of full scale drawing destructive testing found,
in the bolt and mortar interface, with the increase of drawing load, about (15-20)d from bolt hole section
d for bolt diameter are within the scope of shear sliding failure, in the end and the anchor rod body solid
release; In the interface between mortar and surrounding rock, the GFRP bolt is stressed, followed by
the anchor solid, and transferred to the surrounding rock mass.

When Long et al. [8] derived the simplified formula for critical anchorage length of anchor bolt, they
thought, when the displacement of anchor solid top was small, the shear stress between the anchor solid
and the surrounding rock and soil mass gradually develops downward, eventually tends to 0, and reaches
the limit value at the top of the anchor solid.

Zhao et al. [13] found in the field damage test of reinforced anti-floating anchor bolt combined with
ABAQUS numerical simulation software that the vertical influence depth of reinforced anti-floating
anchor on surrounding rock mass is 3.8m; With the increase of depth, the displacement of the bolt system
to the surrounding rock mass is gradually weakened from the outside to the inside and from top to the
bottom.

Bai et al. [18] based on the three full thread GFRP at the scene of the anti-floating anchor rod drawing
destructive testing found, in weathered rock, the stress transfer depth of large-diameter GFRP anchor is
greatly affected by the weathering degree of surrounding rock; The stress transfer depth of GFRP bolt is
affected by the properties of surrounding rock and soil, the length of bolt itself, as well as the diameter
of bolt, the diameter of borehole, the strength of mortar and the shape of thread.

According to the results of finite element analysis, Li [34] found in the process of studying the
interface of a high-strength concrete from the perspective of micromechanics that near the loading end
of the plate, the difference between the stress value on the upper surface and the lower surface of the
plate is very small, and the bending stress is not obvious; in the bonding section between GFRP and
concrete, the stress value of the lower surface is more unstable than that of the upper surface, and the
stress value of the upper surface and the lower surface of the slab appears in a cross shape, but the
difference is very small. When the plate's loading end is unconstrained, the stress value in the plate
decreases with the increase of the distance from the midpoint of the width of the plate. When the loading
end of the plate is entered, the tensile stress value increases with the increase of the distance from the
midpoint of the width of the plate.

4.2. The grip force
Cui et al. [5] through indoor pull-out tests of GFRPP bolts and cement mortar with different anchoring
depths, found that the size of holding force is proportional to the change of anchoring depth; the holding
force is proportional to the change of concrete strength.

Bai et al. [9] through the Qingdao phase 1 subway (line 3) in Ningxia road No. 3 B entrance 6 GFRP
reinforced feasibility of the feasibility and 4 at the scene of full scale drawing destructive testing found,
increasing the bonding length of GFRP bolts at the loading end can prevent brittle shear failure at the
loading end. When the diameter of anchor bolt, length of anchor section and mortar strength are equaled,
the generalized average bond strength of GFRP anti-floating bolt is higher than the steel bolt and mortar.

According to the comprehensive analysis of the test results of the bond performance between fiber
polymer bars and concrete, Gao [32] found that the larger the buried length of fiber polymer bars the
more uneven the bond stress distribution after stress, and the change of the bond strength is inversely
proportional to the buried length when the specimen is damaged.

Zhang et al. [17] found in the field pull-out test that the generalized average bond strength of bolt is
inversely proportional to the change of anchor length in concrete, which has nothing to do with the form
of reinforced anti-floating bolt. The generalized average bond strength of bolts with similar anchoring length in concrete is also similar. The shorter the external anchoring length of the reinforcement anti-floating bolt, the better the bonding performance between the bolt and the concrete can be achieved.

4.3. Displacement

Bai et al. [35] through the twelve full thread root GFRP feasibility and ten reinforced feasibility full scale drawing test was carried out safely draw the conclusion that increase the diameter of the GFRP bolt can effectively restrict the displacement of anchor in the concrete. Reduce the bolt shear stress can produce smaller displacement. Increasing the GFRP bolt anchorage length can effectively limit displacement of anchors in concrete.

When Mou et al. [45] analyzed the deformation of surrounding rock caused by the pulling force on the misfixed segment of ground anchor, the following formulas was obtained.

When the rod body was assumed to be a one-dimensional unit, the displacement change of GFRP anti-floating anchor rod body was:

$$\omega_0 = -\frac{q}{K_{SR}} + \omega _r = \frac{1}{k_{SR}} \frac{dp}{dz} + \omega _r$$

$$\omega _r(z) = \int_0 h \sum_{i=1}^{n} K(R_i, z, \xi) dP(\xi) + \frac{1}{k_{SR}} \frac{dP(z)}{dz}$$

Discrete format:

$$\omega _r = \sum_{j=1}^{n} \left[ K(R_i, z, \xi)(P_{n-i+1} - P_{n-i}) + K(R_i, h,h)(P_{i1} - P_0) + K(R_i, h+h+h)(P_{n} - P_{n-1}) + \frac{1}{\Delta k_{SR}} R_i \right]$$

Where,

$$R_i = \frac{1}{2}(P_{n-i} - P_{n-i-1}) \quad i = 1 \sim n - 1$$

$$R_i = P_{i+1} - P_{i} \quad i = 0$$

$$R_i = P_{i} - P_{i-1} \quad i = n$$

$h$ is buried depth, $P_0$ is the pulling force, $P$ is the axial force inside the bolt, $l$ is the length of the anchorage section, $K_{SR}$ is the tangential stiffness coefficient reflecting the deformation characteristics of the grouting, $R_i$ is the radius of the grouting, $\omega _r$ is the displacement of the rock mass caused by the load acting on the bolt through the grouting shear to the rock mass, and $q$ is the shearing concentration.

Ignoring the presence of slurry (simplified case):

Displacement of rods:

$$\omega _s(z) = \int_0 h K(z, \xi) dP(z)$$

Discrete format:

$$\omega _s = \sum_{j=1}^{n} \left[ K(z, \xi)(P_{n-i+1} - P_{n-i}) + K(z, h,h)(P_{i1} - P_0) + K(z, h+h+h)(P_{n} - P_{n-1}) \right]$$

Chen et al. [1] in shenzhen natatorium and amber richland garden as an example, the feasibility of basic test analysis on breakage types of anti-floating anchor rod in shenzhen area, it found that in the conglomeratic clayey rock, when reaches the design value, the consolidation grouting body intensity of grouting body and boundary shear force is insufficient to resist the effects of the axial force of the applied load, the shear plane place of the anchored body and the foundation soil surface is far less than that of grouting body and the shear strength of interface friction instead. In strong-medium-breeze granite, the displacement of the anchor bolt with a longer anchor length relative to the surrounding rock reaches the maximum value as the external load approaches the limit value. In strongly weathered granite, the bond stress between grouting and surrounding rock increases rapidly with the increase of external load, and the deformation at the interface is larger. In the breezed granite, the stress distribution of the bolt is not uniform, and the stress and deformation at the top of the bolt are the largest.

Luo et al. [7] improved the bond-slip continuous curve constitutive relationship model proposed by predecessors by conducting tensile tests on 9 GFRP bolts with different diameters and bonding performance tests on 27 GFRP bolts with different diameters and surface morphologies,
Rising period $0 \leq s \leq s_u$,

$$\tau = 2 \left( \frac{s}{s_u} \right)^K \left( 1 - \frac{s}{s_u} \right)$$

(8)

Decline period $s_u \leq s \leq s_r$,

$$\tau = \tau_0 \left( \frac{s_r - s}{s_r - s_u} \right)^2 + \tau_0 \left( \frac{s - s_0}{s_r - s_0} \right)^2$$

(9)

Where, $\tau_u$ is the shear stress at the peak point, $s_u$ is the slip corresponding to the shear stress at the peak point, $s_0$ is the slip corresponding to the residual shear stress, and $K$ is the correction factor (0.675 for the threaded bolt, 0.722 for the surface coated with epoxy resin, and 0.877 for the surface polished).

When Bai Xiaoyu et al. [25] analyzed the deformation composition of GFRP anti-floating anchor bolt from the perspective of total deformation, they obtained the formula

Deformation formula of rock and soil mass close to the surface of anchor solid at the anchor hole:

$$\delta_0 = \alpha_0(0, r_0) = \frac{\tau_0 r_0}{G_s \ln\left(\frac{r}{r_0}\right)}$$

(10)

The simplified formula is:

$$\delta = \delta_0 + \delta$$

(11)

Where, $\tau_0$ is the shear stress of the rock and soil mass at the top surface of the anchor solid, $r_0$ is the radius of the anchor solid, $r$ is the vertical distance between a point in the rock body and the axis of the GFRP anti-floating anchor body, and $G_s$ is the shear modulus of the surrounding rock and soil mass.

Zhang et al. [17] found in the field drawing test that at the initial loading stage, the average bond strength rises quickly, the slip is small, and the curves are linear and almost coincide. With the progress of loading, the growth rate of the average cohesive force slows down, while the displacement increases faster, and the curve turns to an inflection point.

5. Prospects for future researches

At present, there are still some deficiencies in the research of GFRP bolt:

(1) At present, there is no clear mechanism of mechanical transfer between GFRP bolt and the soil surrounding the anchor solid;

(2) GFRP bolt durability research, such as the use of GFRP bolt in some special environments will be faced with a huge project whether it can work normally during the service period;

(3) At present, there are few research results on group-anchor effect, but group-anchor effect plays a vital role in structural stability and bearing characteristics;

(4) At present, there is a lack of relevant GFRP stress-strain and bearing capacity specifications;

(5) The attention should be paid to the mechanical transfer mechanism between GFRP and surrounding soil layer, durability research, anchor group effect, formulation, and revision of relevant specifications in the future research of GFRP anti-floating anchors.

6. Conclusion

This paper summarizes the research on the stress-strain relationship of GFRP bolt, bearing capacity transfer characteristics, and the relationship between bolt and rock body:

(1) The stress-strain relationship of GFRP bolt is summarized at home and abroad, and the influence of ultimate bearing capacity, axial stress, shear stress, long-term load (creep) and bending treatment on the stress-strain relationship is respectively summarized.

(2) The load transfer characteristics of GFRP bolt body are summarized and analyzed, and the transfer characteristics of axial stress and shear stress in the bolt are respectively summarized.

(3) The shortcomings of the existing research are summarized.

(4) The possibility of future research is listed.
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