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Anchorage Performance and Interfacial Mechanics Transfer Characteristics of a Composite Anchor Bolt with Different Surface Shape

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Abstract

To solve the deficiency of steel anchor blot in corrosion resistance and flaw of GFRP anchor bolt in fracture resistance, our research group develops a new composite anchor bolt made of steel strands wrapped up with compound fiber resin. To improve the cohesion performance of the composite anchor bolt, pull-out tests of different composite anchor bolts with different groove intervals and depths were made and analyzed. The results show that the pulling resistance of the composite anchor bolt increases with the increase of groove interval and depth, but groove interval and depth have optimal value. Based on elastic mechanics, the cohesion between anchor bolts and anchor bodies and its distribution characteristics caused by axial tension are analyzed and cohesion formula is obtained. By contrast, the experimental result is consistent with the theoretical analysis. Therefore, the surficial change of anchor colts could influence the performance of the composite anchor bolt. The cohesion force and anchorage performance can be improved by changing the surface of anchor bolts. Research results show that the new composite anchor bolt is high-performance material in the civil engineering.

Keywords

Composite Anchor Bolt, Pullout Test, Surficial Shape, Cohesion

1. Introduction

In the late 1950s, the GFRP anchor bolt began to be studied and produced. After decades of development, it has

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been widely applied to correlative fields. For example, the UK has applied MT-J [1] to roadway support in 1990s and the US has researched the cohesion performance of the composite anchor bolt in geotechnical constructions [2]. In 1970s, China began to make use of the GFRP anchor bolt and it had a good application effect in mines of Xuzhou, etc. [3]. The extended and high-strength screw-thread steel resin bolts and prestressed resin anchor bolts [4] have been approved ubiquitously recent years.

The GFRP anchor bolt has a lot of advantages, such as well corrosion resistance and durableness [5], high tensile strength (which is higher than the ordinary rebar), little specific gravity (which is convenient to transport and construct) and a coefficient of thermal expansion which is similar with the concrete. However, the compression resistance and fracture resistance of the GFRP anchor bolt are inferior to the ordinary rebar, and the strength of extension needs to be further enhanced. To improve the performance of the GFRP anchor bolt effectively, composite anchor bolts were made of steel strands which were wrapped up with compound fiber resin. Nevertheless there were some failure phenomena [6]-[8]; for example, the surficial resin was aborted in shear and the joint for anchoring was aborted in tensile during the tensile tests which were conducted by the same anchoring method with ordinary resin rebars because of the high strength of composite anchor bolts. Obviously, the anchoring method of composite anchor bolts still needs some further researches. The study on anchoring performance of composite anchor bolts is conducted to provide a reference for its application to anti-floating or shoring projects.

2. Experiment on Anchoring Performance

The anchoring performance of composite anchor bolts is relative to the diameter and shape of the bolts, the thickness and shear strength of the resin, anchoring length, the property of surrounding soil, etc. [9]-[12]. To study the influence factors and analyze the impact of surficial shape on anchoring performance, a series of laboratory experiments were conducted.

2.1. Method of Experiment

The mainly experiment equipment is WAW-600CkN Electro-hydraulic servo universal testing machine. Its Maximum tension is 500 kN, the largest piston stroke is 250 mm and clamping range for 13 - 40 mm. The tensile experiments of composite anchor bolts are controlled by displacement. The loading speed is set to 0.083 mm/s and the diameter of the specimen is 20 mm. As shown in **Figure 1**, the length of test-piece is 400 mm [13] while the anchorage length is 260 mm. The test-piece is anchored by a 280 mm-long steel tube with spiral grooves. The anchoring agent is blended while conducting the experiment and then pour it into the steel tube evenly to anchor the test-piece.

2.2. The Impact of Groove Spacing to Anchoring Performance

The surface of anchor bolts is grooved by a sander to enhance the cohesion between anchor bolt and anchoring agent.

As the materials for the experiment, the diameters of anchor bolts range from 18.64 mm to 20.40 mm and the diameters of steel strands inside of anchor bolts are 15.2 mm. The anchor bolts are processed into four types which are different on groove spacing. They respectively are 0 mm, 13.25 mm, 23.15 mm, 33.42 mm and the depth of the grooves is 4.05 mm, as shown in **Figure 2**. Three are chosen in each type and there are 12 test-pieces

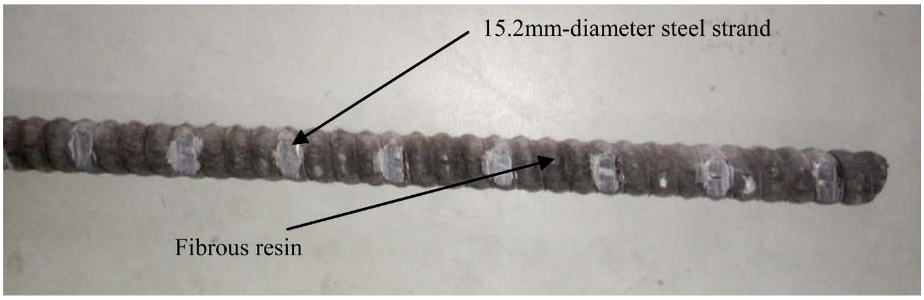

Figure 1. Composite bolt (diameter is 20.4 mm).

in total. The conditions and processing technic of all test-pieces are same. According to the results of experiments, it is turned out that the method of anchoring is reliable and all of the 12 test-pieces are sheared into failure at the interface of anchor bolts and anchoring agent, as shown in **Figure 3**. The experimental data and the tension-displacement curve are obtained as shown in **Table 1** and **Figure 4**.

As shown in **Figure 4**, the ultimate tension of type 2 (groove spacing is 13.25 mm and ultimate tension is 205.9 kN) is 6.44% higher than the one of type 1 (groove spacing is 0 mm and ultimate tension is 193.4 kN), while the ultimate tension of type 3 (groove spacing is 23.15 mm and ultimate tension is 201.4 kN) is 2.20% lower than the one of type 2. It decreases to 179.2 kN when the groove spacing increases to 33.42 mm (type 4) and the amplitude of decrease is 12.9%. It is obvious to see the uplift resistance of composite anchor bolts firstly increases and then decreases with the increase of groove spacing.

It can be seen from the failure of the 12 test-pieces that the failure form between anchor bolts and anchoring agent has been changed by the groove spacing. The anchoring agent is aborted in shear before adhesion between

Figure 2. Test-pieces different on groove spacing.

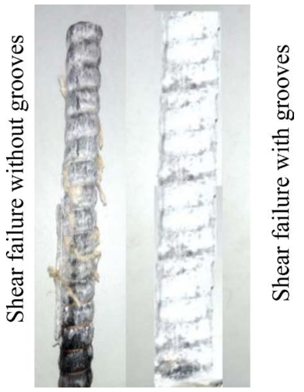

Figure 3. Shear failure.

Table 1. The experimental data of different groove spacing bolts in pull-out test.

Number	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Groove spacing/mm	0	0	0	13.25	13.25	13.25	23.15	23.15	23.15	33.42	33.42	33.42
Groove depth/mm	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05	4.05
Bolt diameter/mm	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.4	18.64 /20.4	18.64 /20.4
Anchorage length/mm	260	260	260	260	260	260	260	260	260	260	260	260
Temperature/˚C	22	22	22	22	22	22	22	22	22	22	22	22
Ultimate tension/KN	201.1	191.9	187.3	208.1	203.6	205.9	206.2	203.6	194.5	185.3	171.6	180.7
Ultimate displacement/mm	12.5	9.99	11.8	11.5	14.4	15.4	18.7	16.2	19.4	21.3	21.2	22.4

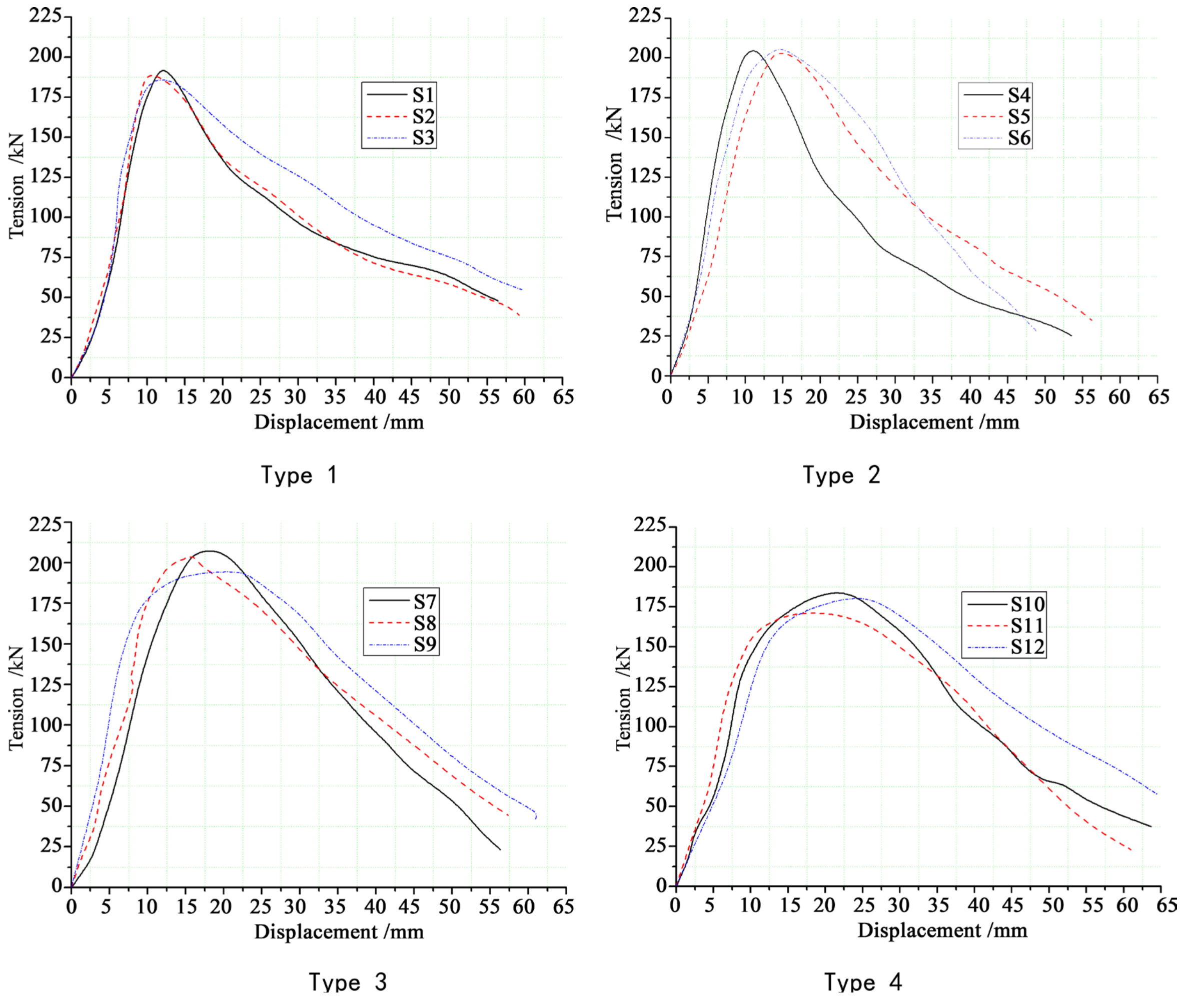

Figure 4. The tension-displacement curve of test-pieces with different groove spacing.

anchor bolts and anchoring agent is invalid when the groove spacing is 33.42 mm. It enhances the adhesion effectively that the anchoring agent takes more shear with the decrease of groove spacing. The resin never break away from the inside steel strand during the experiments. It is reasonable that the groove spacing is designed as 23.15 mm taking various factors into consideration.

2.3. The Impact of Groove Depth on Anchoring Performance

It can be researched that the impact of groove depth on anchoring performance based on the above experiment. The anchor bolts are processed into another four types which are different on groove depth. They respectively are 0.88 mm, 2.02 mm, 3.04 mm, 3.95 mm and the spacing of the grooves is 23.15 mm. Three are chosen in each type and there are 12 test-pieces in total. The conditions and processing technic of all test-pieces are same with the above experiments'. The experimental data, the tension-displacement curve and tension-groove depth are obtained as shown in **Table 2**, **Figure 5** and **Figure 6**.

When the groove depth is 0.88 mm the ultimate tension is 182.3 kN which is minimum while the ultimate tension is 208.3 kN which is maximum when the groove depth is 3.95 mm. It is improved 14.3% by 26.0 kN. As shown in **Figure 6**, the ultimate tension increases with the increase of groove depth.

3. Mechanical Analysis of the Composite Anchor Bolt

As we known in material mechanics, the shearing resistance of the material with the constraint conditions can be improved effectively. The shape of composite anchor bolts has a significant impact on their uplift resistance. So

Table 2. The experimental data of different groove depth bolts in pull-out test.

Number	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
Groove spacing/mm	23.15	23.15	23.15	23.15	23.15	23.15	23.15	23.15	23.15	23.15	23.15	23.15
Groove depth/mm	0.88	0.88	0.88	2.02	2.02	2.02	3.04	3.04	3.04	3.95	3.95	3.95
Bolt diameter/mm	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.40	18.64 /20.4	18.64 /20.4	18.64 /20.4
Anchorage length/mm	260	260	260	260	260	260	260	260	260	260	260	260
Temperature/˚C	22	22	22	22	22	22	22	22	22	22	22	22
Ultimate tension/kN	175.6	179.5	183.9	186.5	190.3	187.6	201.2	200.9	200.6	208.9	207.8	208.1

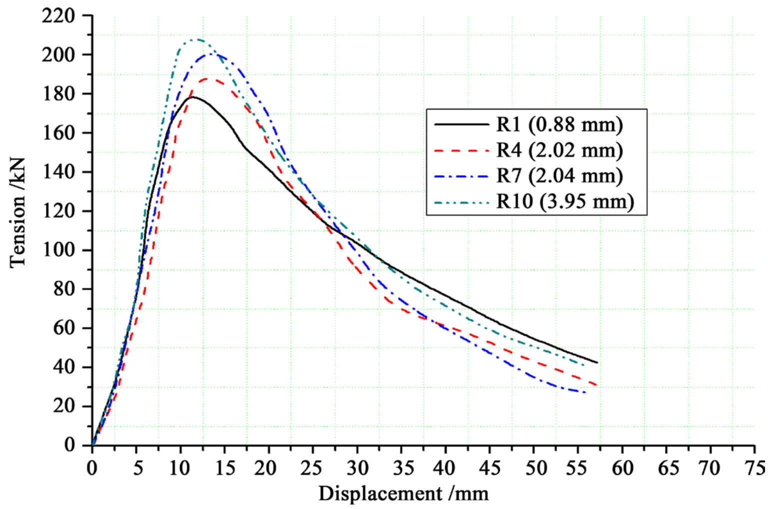

Figure 5. The tension-displacement curve of test-pieces with the change of groove depth.

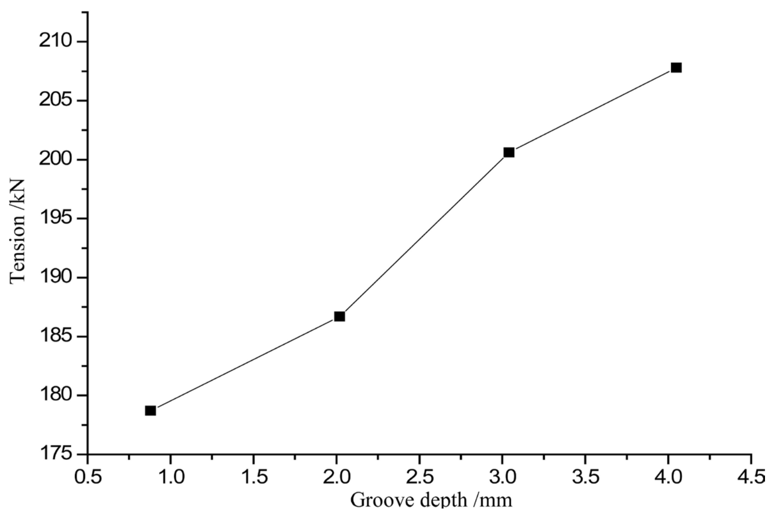

Figure 6. Relationship between tension and groove depth.

it is necessary to study the impact of surficial shape on anchoring performance of composite anchor bolts.

Take a micro segment from the axis of the anchor bolt and analyze its stress state as shown in **Figure 7**. $\sigma_{ra}(z)$ and τ stand for respectively the micro segment' normal stress and shear stress while σ_z stands for the axial stress of the anchoring body. To facilitate the mechanical analysis of the section of anchorage, make the following assumptions: 1) all materials are continuous, homogeneous and isotropic linear elastic body; 2) the axial stress σ_z distributes in the transect of the anchoring agent uniformly; 3) the anchor bolt and the anchoring agent deform simultaneously in the radial direction in the range of elastic deformation.

As shown in **Figure 8**, F is the tension of the anchor bolt. And then the axial stress of an arbitrary point M (0, 0, z) on the anchoring agent is

$$F(z) = F - \int_0^z 2\pi r_a \tau(z)\,\mathrm{d}z \tag{1}$$

The axial strain of M is

$$\sigma_z(z) = \frac{F(z)}{A_a} = \frac{F - \int_0^z 2\pi r_a \tau(z)\,\mathrm{d}z}{\pi r_a^2} \tag{2}$$

In the formula above, r_a stands for the radius of the anchoring agent and A_a stands for its cross-sectional area.

According to the Hooke's law, the radial strain ε_{ra} of point M in the anchoring agent is

$$\varepsilon_{ra}(z) = \frac{1}{E_a}\left[\nu_2\sigma_z(z) - (1-\nu_2)\sigma_{ra}(z)\right] \tag{3}$$

In the formula (3), ν_2 stands for the Poisson ratio of the anchoring agent and E_a stands for its elasticity modulus converted.

The shear in the interface meets with the Mohr-Coulomb criterion, so it is

$$\tau(z) = c + \sigma_{ra}(z)\tan\varphi \tag{4}$$

Based on the theory of elastic mechanics, the radial strain of radius r in a anchoring agent (whose length is z) when a circular aperture is loaded a radial stress $\sigma_{ra}(z)$ is

$$\varepsilon_{rr}(z) = \frac{1+\nu_1}{E}\frac{r_a^2}{r^2}\sigma_{ra}(z) \tag{5}$$

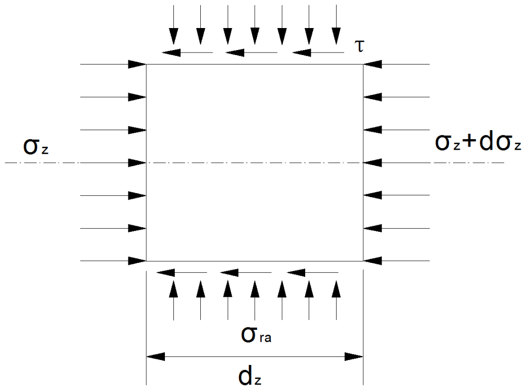

Figure 7. Mechanical analysis on the stress state of the micro segment.

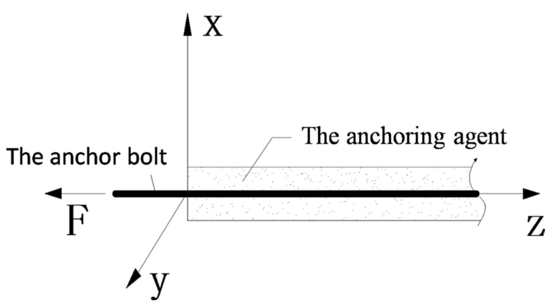

Figure 8. Calculation diagram.

In the formula (5), E and ν_1 stand for the elasticity modulus and poisson ratio of the anchoring agent with constraint conditions respectively.

On the basis of deformation and coordination conditions,

$$\varepsilon_{rr}\big|_{r=r_a} = \varepsilon_{ra} \tag{6}$$

Synthesize the formula (3), formula (5) and formula (6). And the compatibility equation of deformation is

$$\left(\frac{1-\nu_2}{E_a}+\frac{1+\nu_1}{E}\right)\sigma_{ra}(z)=\frac{\nu_2}{E_a}\sigma_z(z) \tag{7}$$

$$\sigma_{ra}(z)=\frac{E\nu_2}{E_a(1+\nu_1)+E(1-\nu_2)}\sigma_z(z) \tag{8}$$

When $K=\dfrac{E\nu_2}{E_a(1+\nu_1)+E(1-\nu_2)}$, there is

$$\sigma_{ra}(z)=K\sigma_z(z) \tag{9}$$

Synthesize the formula (2), formula (4) and formula (9) and there is

$$\sigma_{ra}(z)=K\frac{\left(F-\int_0^z 2\pi r_a\tau(z)\mathrm{d}z\right)}{\pi r_a^2} \tag{10}$$

A differential equation can be obtained by a simultaneous of formula (4) and formula (10).

$$\sigma'_{ra}(z)=-A\sigma_{ra}(z)-B \tag{11}$$

In formula (11), $A=\dfrac{2K\tan\varphi}{r_a}$, $B=\dfrac{2Kc}{r_a}$.

The general solution of formula (11) is

$$\sigma_{ra}(z)=\frac{C\exp(-Az)-B}{A} \tag{12}$$

C is a constant in formula (12).

There is a boundary condition: $$\sigma_z(z)=\frac{F}{\pi r_a^2},\quad z=0 \tag{13}$$

According to the formula (9), $$\sigma_{ra}(z)=K\frac{F}{\pi r_a^2},\quad z=0 \tag{14}$$

Substitute formula (14) into formula (12), $$C=\frac{KFA}{\pi r_a^2}+B \tag{15}$$

The following formulas can be obtained.

$$\sigma_{ra}(z)=\frac{KF}{\pi r_a^2}\exp(-Az)+\frac{B\left(\exp(-Az)-1\right)}{A} \tag{16}$$

$$\sigma_z(z)=\frac{F}{\pi r_a^2}\exp(-Az)+\frac{B\left(\exp(-Az)-1\right)}{AK} \tag{17}$$

$$\tau(z)=c+\left(\frac{KF}{\pi r_a^2}\exp(-Az)+\frac{B\left(\exp(-Az)-1\right)}{A}\right)\tan\varphi \tag{18}$$

It can be obtained by formula (16)-(18) that the stress and its distribution between the anchoring agent and the anchor bolt connect with some factors such as the stress of the anchor bolt, the radius, elasticity modulus and poisson ratio of the anchoring agent, etc. Therefore, it is effective to enhance the cohesion between anchor bolt and anchoring agent by the method of changing the surficial shape of the anchor bolt. Thereby the anchoring performance can be improved obviously. The analysis above is the same with the experiment result.

4. Conclusions

1) As for the groove spacing, the uplift resistance of composite anchor bolts firstly increases and then decreases with the increase of groove spacing. It is reasonable that the groove spacing is designed as 23.15 mm taking various factors into consideration. The result provides a reference for the surficial treatment to improve the anchoring performance.

2) The anchoring performance of the composite anchor bolt increases with the increase of groove depth. It is reasonable to design the groove depth as 3.95 mm. The mechanical property can be improved by the groove depth. It is a pretty way to make the anchoring performance more advanced.

3) It indicates that the composite anchor bolt has a good overall performance that the resin never breaks away from the inside steel strand during the experiments.

4) On the condition that there is little impact on the strength of extension of the anchor bolt, it is a very effective way to improve the anchoring performance by changing the surficial shape of the anchor bolt which has been confirmed by experiments and theoretical analysis.

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