Experimental Investigation on the Mechanical Properties of a Noval Bond-Type Anchorage for Carbon Fiber Reinforced Polymer Tendons

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Abstract. In order to effectively alleviate the stress concentration phenomenon of the inner-cone bond type anchorages and improve the ultimate anchoring capacity of the anchorages, a new kind of arcuate-cone bond type anchorage for carbon fiber reinforced polymer (CFRP) tendons was designed. The stress distribution curves, load-slip curves and failure modes of anchorages are obtained by tension test of a group of inner cone and arcuate cone anchors with different parameters. According to the test results, the influence of anchorage types, inclination angles and radius of arc on anchorage performance is analyzed. The results show that ultimate anchoring capacity is directly proportional to the slip between anchor cup and grout during loading. The slip of arcuate cone anchorage is larger than that of inner-cone anchorage, and the anchor with smaller inclination angles of anchor cup slips larger. The ultimate anchoring capacity of the novel arcuate cone bond-type anchorages is larger than that of the traditional inner cone anchorages, and the phenomenon of stress concentration on the surface of CFRP tendons is effectively alleviated by using arcuate cone anchorages.

Keywords. CFRP tendon, bond-type anchorage, arcuate cone, experimental investigation, anchoring capacity, stress distribution, load-slip curve.

1. Introduction

Carbon fiber reinforced polymer (CFRP) has been widely applied in civil engineering due to its advantages of light weight, high tensile strength and corrosion resistance [1-4]. CFRP is considered to be a good alternative to steel for some components that need to work in humid and corrosive environments. However, as an anisotropic material, the transverse shear strength of CFRP is significantly lower than its axial tensile strength. The traditional anchorage systems for steel tendons will damage the surface of CFRP reinforcement, reduce its tensile strength and lead to premature failure. Therefore, it is necessary to design an anchorage system for CFRP tendons.

Up to now, there are two kinds of CFRP tendon anchorage systems, which have been developed by researchers, which are mechanical anchorage and bond-type anchorage. On the one hand, the stress concentration phenomenon exists on the load end of inner cone anchorage, and the high peak stress may lead to premature failure of the tendons; on the other hand, the surface of the CFRP tendon is vulnerable to damage. Therefore, the research on both mechanical and bond-type anchorages is committed to solve these two problems.

The mechanical anchorage is usually composed of steel anchor cup and metal wedge. The anchoring principle is to anchor the reinforcement by the extrusion force produced by the wedge [5].
Hence, the biggest disadvantage of mechanical anchorage is that the greater the load, the more easily the tendons will be damaged. In order to settle this problem, a layer of soft metal casing was added on the surface of CFRP tendons [6]. Campbell et al. [7] proposed a wedge anchorage and analyzed its mechanical properties. The results show that by setting the angle difference between barrel and the metal wedge, the stress concentration can be alleviated.

The bond-type anchorage is mainly composed of a steel sleeve, filling materials and CFRP tendons. Since the stiffness of filling material is small, the surface of the reinforcement will not be damaged, so bond-type anchorage is more suitable for anchoring CFRP tendons in comparison with mechanical anchorages [8]. The original bond-type anchorage is straight anchorage, which has low anchoring capacity. Therefore, the engineers design the inner cone anchorage combining the advantages of bond-type anchorage and mechanical anchorage [9]. The ultimate anchoring capacity of the inner cone bond-type anchorage is composed of the chemical bond force and the grout extrusion force, but at the same time, the phenomenon of stress concentration also appears at the loading end. Meier et al. [10] found that the use of variable stiffness material as grout can make the stress distribution more uniform and improve the anchoring capacity.

In order to alleviate the stress concentration phenomenon and improve the ultimate anchoring capacity, a new type of arcuate cone bond-type anchorage is designed based on the traditional inner cone anchorage. Through the tension test of 8 kinds of inner cone type and arcuate cone type anchorage with different parameters, the stress distribution, load-slip curve and failure mode of anchors are obtained, and the influence of anchor type, arc radius, anchorage length, inclination angles on anchorage performance is studied.

2. Experimental Program

2.1. Design Concept
Due to the large stress peak at the loading end of traditional inner cone anchorages, the design of arcuate cone anchorages is to make the surface stress distribution more uniform along the axial direction.

When the straight type anchors were used, the surface stress of CFRP tendons is distributed smoothly. Therefore, it can be inferred that the inclination angle of barrel is related to the stress distribution. Thus, a novel arcuate cone bond-type anchorage is designed, whose section is part of the circular arc as shown in figure 1.

![Figure 1. Section of arcuate cone bond-type anchorage.](image)

2.2. Specimen
CFRP tendons with diameter of 8 mm are used in this tension test, and Lica 300 epoxy resin adhesive was used as filling material. The properties of materials are summarized in table 1.
Table 1. Material parameters of specimen.

| Material          | Tensile strength (MPa) | Compressive strength (MPa) | Elastic modulus (GPa) | Axial Poisson’s ratio | Radial Poisson’s ratio |
|-------------------|------------------------|----------------------------|-----------------------|-----------------------|------------------------|
| CFRP tendons      | 2000                   | --                         | 140                   | 0.27                  | 0.02                   |
| Lica300 adhesive  | 40.1                   | 73.6                       | 2.61                  | 0.25                  | 0.25                   |
| steel             | 345                    | 345                        | 206                   | 0.3                   | 0.3                    |

Eight kinds of inner cone type and arcuate cone type anchorage with different parameters were tested. The bond length of anchors was 200 mm or 300 mm and the inclination angles were \( \arctan(0.06) \) and \( \arctan(0.09) \). The section size of anchors are shown in figure 2. The inner cone anchorages were labeled as “IC + bond length + (tanγ)”, and acuate anchors were labeled as “AC + bond length + radius of arc + (tanγ)”, respectively.

![Figure 2. Section size of eight kinds of anchorage.](image)

There were three steps in the preparation of the specimens. The first step is to apply strain gauges to the surface of CFRP tendons, clean the inner surface of barrels with alcohol, and spray the cleaned surface with epoxy resin release agent. In the second step, the barrels were assembled with tendons, and Lica300 epoxy resin adhesive is poured with an injection gun. In the last step, the prepared specimens were cured naturally at ordinary temperature for 24 h, then the anchors were wrapped with a heating plate and cured for 5h at 80°C to achieve the designed strength of the filling material.

2.3. Test Setups and Procedure

The test setups of the specimen are shown in figure 3, and the load was carried out by a jack in stages. Before formal loading, the load is preloaded by 5kN, then unloaded to 0, and then loaded formally by 5kN per stage. If the CFRP tendons slip significantly during loading but anchorages can still hold the load, it will continue to load until the anchor was destroyed.
The main purpose of tension test is to obtain the load-slip curve and stress distribution on the surface of CFRP tendons. During the test, the stress distribution was measured by the strain gauges installed on the surface of tendons, and the location of the strain gauges are shown in figure 4. A dial indicator installed at the free end was used to estimate the slip of CFRP tendons, and all data were recorded by DH3820.

3. Test Results and Discussion

3.1. Failure Modes

Three different failure modes are shown from left to right in figure 5, which are pull-out failure, partial debonding failure and tensile fracture of CFRP tendons. The failure modes of each specimen are shown in table 2.

| Specimen          | Failure Mode                  |
|-------------------|-------------------------------|
| IC200(0.06)       | Partial debonding failure     |
| IC200(0.09)       | Pull-out failure              |
| IC300(0.06)       | Pull-out failure              |
| IC300(0.09)       | Pull-out failure              |
| AC200-r1673(0.06) | AC200(0.09)-r1120             |
| Partial debonding failure | Partial debonding failure |
| AC300-r2656(0.06) | AC300-r1680(0.09)             |
| Partial debonding failure | Tensile fracture of CFRP tendons |

Figure 5. Three failure modes.
The typical failure mode of anchorage is pull-out failure of tendons, and the failure mode of anchorage is related to ultimate anchoring capacity of specimen. Through the analysis of table 2, it can be seen that, for the same bond length and the same inclination angle, the arcuate cone type anchors are more prone to partial debonding failure. In addition, for the same type of anchorage with same bond length, the larger the inclination angle is, the more likely to occur pull-out failure.

3.2. Load-Slip Curves of CFRP Tendons

The slip induced by CFRP tendons is divided into two parts, one is the initial slip in the preloading stage, and the other is the slip during the loading process, that is, the slip in the load-slip curve. The load-slip curve of CFRP bars is often used to express the anchorage performance of bond type anchors.

It can be seen from figure 6 that the load-slip curves of each specimen are nonlinear. In the early stage of the loading process, the growth rate of the slip of each specimen is relatively uniform. However, when the failure is about to occur, the slip amount of CFRP bars will increase suddenly with the decrease of load.

![Figure 6. Load–slip curves of each anchorage.](image)

In addition, the load slip curves of different specimens are not the same, which indicates that the load slip curve is affected by the design parameters such as anchor type, inclination angle of barrel and bond length.

By comparing the load-slip curves of anchors with different inclination angles in figure 6, it can be seen that when the load is the same, the slip is smaller for the specimen with larger inclination angle of the inner surface.

3.3. Stress Analysis of CFRP Tendons

The stress distribution on the surface of CFRP tendons is the most intuitionistic data for analyzing the anchoring performance of bond type anchorage. However, when the specimen is close to failure, the interface between tendon and filling material tends to produce slip, which makes strain gauges fail. Therefore, only the stress distribution in the early stage of loading process is analyzed.

The original purpose of the design of arcuate cone anchorage is to alleviate the stress concentration phenomenon of traditional inner cone anchorage at the loading end. Therefore, the stress distribution curves of IC200 (0.06) and AC200-r1673 (0.06) were compared. The distribution curve of surface stress was measured, as shown in figure 7.
Figure 7. Surface stress distribution curve of IC200 (0.06) and AC200-r1673 (0.06).

It can be seen from figure 7 that the stress distribution curves in the anchor zone of CFRP bars with inner cone and arcuate cone are both nonlinear. For the inner cone anchorage, there is obvious stress concentration at the loading end, and the peak stress is almost twice as much as that in the middle of the anchor zone.

Compared with the traditional inner cone anchorage, the peak stress of the arcuate cone anchorage is significantly reduced and transferred to the interior of the anchor zone. At the same time, the stress distribution of the arcuate cone anchorage is more uniform in the whole anchor zone.

4. Conclusions

(1) The novel arcuate cone anchorage has successfully used to anchor CFRP tendons. The failure mode of the tension test of the arcuate cone anchorage is tensile failure of CFRP bars, and the anchorage efficiency is more than 0.9.

(2) The ultimate anchoring capacity of the novel arcuate cone bond-type anchorage is generally higher than that of the traditional inner cone anchorage.

(3) The slip of CFRP tendons is related to the type of anchorage. When the bond length and the inclination angle is the same, the slip of arcuate cone anchorages is greater than that of inner cone anchorages.

(4) Compared with the inner cone anchorage, the new arcuate cone anchorage can effectively alleviate the stress concentration and reduce the peak stress at the loading end.

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