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Experimental investigation on the mechanical properties of a bond-type anchor for carbon fiber reinforced polymer tendons

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) has gained popularity in civil engineering applications due to its high tensile strength, light weight, corrosion resistance, and fatigue resistance. However, the anchorage of CFRP tendons has been a challenge due to the relative low transverse shear strength of CFRP. To study the mechanical properties of bond-type anchor for CFRP tendons, straight-type, inner-cone-type, and composite-type anchors were developed in this study. The bond-slip behavior of CFRP tendons inside anchors and multiaxial stresses of the steel sleeve were experimentally tested. The effects of anchor type and length on the anchorage performance of CFRP tendons were studied with the focus on the anchoring mechanism. Test results demonstrate that the composite-type anchor exhibits the most reliable load-transfer mode and can eliminate the notch effect occurred in the inner-cone-type anchor. The peak bond stress initially occurs at the loading end of the anchor and gradually moves to the free end of the anchor as the load increases. This is related to the gradual failure of chemical adhesive between the CFRP tendon and the colloid. Besides, bond-slip relationship of CFRP tendon inside anchor is nonlinear. The slippages of CFRP tendons are initially small but increase quickly with increasing load. When approaching failure, the slippages increased significantly. In addition, the slippage of the anchor with scattered-end tendon is smaller than that with non-scattered-end tendon, indicating that the anchor with scattered-end tendon has superior bonding property.

1. Introduction

Carbon fiber reinforced polymer (CFRP) exhibits many attractive advantages, including excellent corrosion resistance, high tensile strength, light weight and outstanding anti-fatigue performance. Hence, it has been widely studied and applied in civil engineering [1–6]. However, the transverse shear strength of CFRP is relatively low compared to its tensile strength. The traditional steel tendon anchorage system may damage the surface of CFRP tendon and thus may cause premature failure. Therefore, traditional anchors are unsuitable for CFRP tendons, whether as prestressed tendons, stay cables, or suspension cables.

Numerous investigations and applications of anchorage systems for CFRP tendons have been reported in Japan, North America, and China [7–9]. Based on anchoring mechanism, CFRP tendon anchorage systems can be divided into two categories: mechanical anchor and bond-type anchor [8,10]. Clip-type and cone-plug anchor are classified as mechanical anchor. Premature failure may occur as a result of the high extrusion forces of sleeve to clip or cone during loading process. Some authors have investigated mechanical anchors through experiments or finite element method (FEM). Al-Mayah et al. [11–12] proposed a simplified wedge-shaped anchor and analyzed stress distribution on the surface of CFRP tendons using FEM. Campbell et al. [13] proposed a wedge anchor and evaluated its mechanical properties under static and cyclic loading through numerical methods and testing. Elrefai et al. [14] tested the fatigue property of a novel wedge-shaped anchor.

In the bond-type anchor, shear force is transferred through bond stress at the interface, thus preventing excessive stress concentration. Therefore, bond-type anchor is more suitable for anchoring CFRP tendons in comparison with the mechanical anchor. A resin or cementitious matrix is normally used as the filling material. Zhang and Benmokrane [15,16] analyzed the anchorage mechanism and conducted the pull-out test of bond-type anchors filled with a cementitious matrix. They reported that the pull-out capacity of the anchor was influenced by the performances of the bonding material and the surface characteristics of the tendons. Germany DSI Company developed the DYWICARB anchoring system and conducted the static and dynamic tests of this system which anchoring several CFRP tendons [17].

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Table 1
Summary of physical and mechanical properties of 7 mm diameter CFRP tendons.

Nominal diameter [mm]	Specific gravity	Tensile strength [MPa]	Young's modulus [GPa]	Ultimate strain [%]	Thermal expansion [10^{-6}/°C]	Relaxation rate [%]
7	1.6	2250	176	1.44	0.68	2–3

Fig. 1. The scattered-end of CFRP tendon.

Table 2
Summary of mechanical properties of Lica subject to varying environmental conditioning [20].

	Shear strength [MPa]					Tensile strength [MPa]	Compressive strength [MPa]	Elastic modulus [MPa]
Condition	23 ± 2 °C	50 cycles freeze-thaw	2000 h aging	168 h soaking	4 h baking at 80 °C	23 ± 2 °C	23 ± 2 °C	23 ± 2 °C
Result	24.3	19.7	23.0	20.5	22.1	40.1	73.6	2610

Puigvert [18] predicted the fatigue and creep properties of bond-type anchors by FEM and verified the predictions with the test results. Mei et al. [19] conducted a test on a CFRP cable anchor with a high anchorage capacity and applied these CFRP cable anchors to the first cable-stayed bridge with CFRP cables in China [8,20]. Fang et al. [21–24] reported a bond-type anchorage system for multi-rod CFRP tendons with a bonding medium of ultra-high performance reactive power concrete (RPC) and applied this anchorage system as ground anchorage of side hangers in the Aizhai Bridge in China. Fan et al. [25–26] performed pull-out tests on CFRP ground anchors with single-strap and two-strap ends, respectively. Wang et al. [27] proposed a novel anchor for multi tendons and optimized the key factors that affect anchor behaviors using FEM. Wu et al. [28] presented an analytical solution for predicting the maximum pull-out load of FRP rods embedded in steel tubes filled with cement grout. Hou et al. [29] and Cai et al. [30] experimentally investigated the performance of bond-type anchor with single and multiple CFRP tendons. Generally, it is interesting to investigate the load-slip relationship and bond stress distribution of CFRP tendons. Moreover, there is limited research available on the bond stress distribution of bond-type anchors for CFRP tendons.

In this study, an experimental investigation is conducted to study the mechanical properties of the bond-type anchors for CFRP tendons. Three types of bond-type anchors, including straight-type, inner-cone-type and composite-type, were tested and compared. The stress distribution and bond-slip behavior of CFRP tendon during loading process were characterized. Rosettes strain gauges were attached on the surface of the steel sleeve to investigate the stress distribution of the anchor sleeve. To improve the bond strength of anchor, CFRP tendons with scattered-end in the anchor are proposed and tested.

2. Experimental program

The main aims of this experimental program were to study the stress distribution and bond-slip behavior of CFRP tendons inside anchors as well as the stress variation in the steel sleeves during loading process. The rosette strain gauges were used to estimate the stress variation in the CFRP tendons and the steel sleeve. The differences in the mechanical properties of straight-type, inner-cone-type, and composite-type anchors for CFRP tendons were analyzed and compared. In addition, CFRP tendons with or without scattered-end in the anchorage system were studied.

2.1. Specimen

2.1.1. CFRP tendons

The CFRP tendons were composed of pitch-based carbon fibers and epoxy resin. The tendons had indented surfaces to provide interlock and improve bond strength. The physical and mechanical properties of the tendons are obtained from the manufacturer and listed in Table 1. The end of one tendon was scattered, as shown in Fig. 1.

2.1.2. Filling material

Lica, a commercial resin matrix, was used as filling material. The mechanical properties of the resin under various environmental conditions including 50 freeze-thaw cycles, 2000 h of accelerated aging, 168 h of soaking in a water bath, and 4 h of baking in an oven at 80 °C, were provided by the manufacturer and are summarized in Table 2.

2.1.3. Bond-type anchors

Three series of bond-type anchors, including straight-type, inner-cone-type and composite-type anchor, were proposed and tested as shown in Fig. 2. The bond length of anchors in the first and third series was 300 mm, while the bond length of anchors in the second series was 380 mm. The straight anchor was an anchor sleeve with the constant internal diameter along the whole length, while the inner-cone anchor had the internal diameter of the sleeve varied gradually along the bond length. A composite anchor was a compound of a straight zone at the loading end and an inner- cone zone at the free end. There is only one specimen in the third series of anchor, which had CFRP tendon with scattered-end. Straight, inner-cone and composite anchors in the first series were labeled as ZT300, NZ300 and FH300, respectively. In the second series, they were labeled as ZT380, NZ380 and FH380. The anchor in the third series was labeled as FH300S. A glue injection gun was used to mix and grout the colloid as shown in Fig. 3.

2.2. Test setups and procedure

The test setups of the specimens in the first and second series and in the third series are shown in Figs. 4 and 5, respectively. Strain gauges were attached to the surface of CFRP tendons in the free zone and the bonded zone to estimate the tensile stress of the CFRP tendon. Rosettes strain gauges were attached on the surface of the steel sleeve to assess the stress variation of the steel sleeve along the longitudinal direction. The arrangement of the strain gauges and the rosettes strain gauges are