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An experimental study on bond-type anchorages for carbon fiber-reinforced polymer cables

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HIGHLIGHTS

- Large CFRP cable specimens tested with up to 16 Leadline tendons.
- Failure of new resin matrix bond-type anchor controlled by tendon rupture.
- Three specimens tested under varying sustained load duration.
- The proposed bond-type anchor was successfully used in an actual bridge.

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ABSTRACT

It is well-known that the axial performance of carbon fiber-reinforced polymer (CFRP) cables is excellent, while the lateral compression and shear strengths are low. Thus, traditional steel cable anchorages cannot be used for CFRP cables due to the local crushing failure mode that would develop. Hence, a new bond-type anchorage filled with resin was proposed and five CFRP cables were fabricated with the new anchorage, which were tested statically to failure in tension. The tensile capacity, bond strength and pullout behavior of the new anchorage for CFRP cables were observed experimentally and are presented in this paper. The load–slip behavior of the new anchorage, sustained loading effect, load–deformation curves and the stress variation between tendons in the cables are also presented and discussed. Tensile fracture of the tendons was observed for all the five cables tested with efficiency coefficients all greater than 1.00. The tensile strength and overall performance achieved by the anchorage and CFRP cable system satisfied the design requirements for use in an experimental cable-stayed bridge constructed in China.

1. Introduction

External prestressing cables, such as those used in cable-stayed bridges are prone to corrosion and fatigue deterioration [1]. Further, due to the relatively higher self-weight of steel cables it is increasingly difficult to erect steel stay cables for the current trend of super- or ultra-long spans exceeding 1000 m. Carbon fiber-reinforced polymer (CFRP) cables are therefore an ideal alternative to overcome these problems associated with traditional steel cables. In particular, the non-corrosive characteristics are desirable, including the high tensile strength and stiffness, light weight, and excellent fatigue resistance. Most significantly, the reduction in cable weight facilitates handling and field installation compared to steel. Hence, cable-stayed bridges using CFRP cables have been built in several countries including Switzerland, Japan, Denmark, and the United States [2,3]. The first cable-stayed bridge using CFRP cables constructed in China was the Xishan Pedestrian Bridge at Jiangsu University, which was designed and studied at Southeast University [4].

However, the CFRP cables are comprised of tendons that are anisotropic and more sensitive to transverse stress and notch effect compared to steel. The tensile strength in the direction of the fibers is high, while the lateral compression and shear strengths are low. Traditional anchorages used for steel strands, such as wedge-type anchorages, may cause a premature failure if any notching of the CFRP tendons occurs. Thus, traditional anchors are not appropriate for use with CFRP tendons. Therefore, it is necessary to develop and use an anchorage system that does not damage the CFRP tendons.

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Table 1
Summary of physical and mechanical properties of 7.9 mm diameter CFRP Leadline rod.

Data source	Nominal diameter [mm]	Effective cross section [mm^2]	Specific gravity	Tensile strength [MPa]	Young's modulus [GPa]	Ultimate strain [%]	Thermal expansion [10^{-6}/°C]	Relaxation rate [%]
Manufacturer	7.9	46.1	1.6	2600 (2250)	147	1.6 (1.44)	0.68	2–3
Test	–	–	–	2434	162	1.47	–	–

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

	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

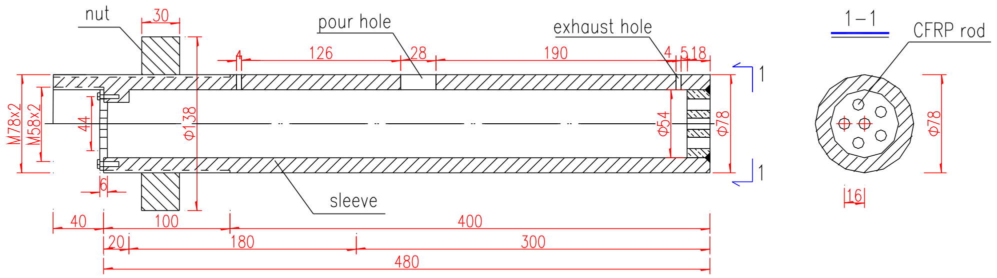

Fig. 1. Schematic of the resin sleeve (RS) anchor.

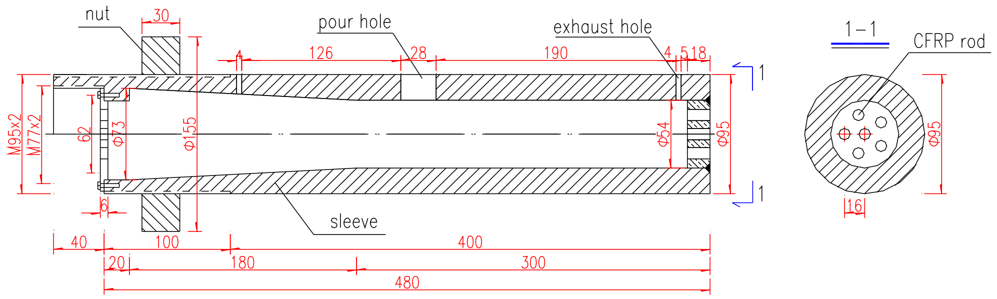

Fig. 2. Schematic of the composite type (CT) anchor.

Various anchorage systems for CFRP tendons have been developed and investigated over the last two decades [5–8]. Based on the anchorage principle used, they can be classified into two types, bond-type or mechanical anchorages, depending on the load transfer mechanism used. Bond-type systems anchor the tendons through adhesion between the tendon and the adhesive. Conversely, mechanical systems use friction to anchor the tendons. Bond-type systems consist of a steel sleeve inside which single or multiple tendons are bonded by a resin or cementitious matrix. The performance of bond-type systems depends on the surface characteristics and bonded length of the tendon, the properties of the bonding matrix, and the geometry of the steel sleeve [7,9–15]. The bonding mechanism in some bond-type anchorage systems with different FRP tendons has been systematically studied [16,17]. Nanni et al. studied some commercially available anchorage systems and tested their ultimate tensile strength and tensile properties during sustained loading [18]. Benmokrane et al. analyzed the mechanism of how bond-type anchorages work with FRP tendons [16]. In general, bond-type systems are shown to be reliable for anchoring CFRP tendons. They can be easily installed without the need for high technical competency. However, most of the tests described here used a cementitious matrix, and most of the anchorages only anchor a single, or a few, CFRP tendons.

Several mechanical anchorages have also been proposed for CFRP tendons, such as the plug and cone, clamp, and split-wedge anchorages [19–24]. The split-wedge anchorage system is the most widely used system in civil engineering applications. The performance of a split-wedge anchorage depends on the friction activated between the tendon and the wedges. Besides experimental research, other researchers have undertaken numerical or mathematical analyses of split-wedge anchorage systems [21,25–28]. Al-Mayah et al. investigated the contact stress distribution on CFRP tendon surfaces in a system through finite element and mathematical analyses [22,25–26]. In order to improve the grip, the wedges and the tendon may be treated with a rough surface. Split-wedge anchorages have many attractive characteristics for application in prestressed concrete structures, such as compactness, reusability,