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Review

# Anchorage systems of CFRP cables in cable structures—A review

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## HIGHLIGHTS

- Several available anchorage systems of CFRP cables in cable structures are reviewed.
- Experimental, FE and analytical studies of anchorages are illustrated.
- New research areas of CFRP cable anchorages are introduced.
- Some focus of research for CFRP cable anchorages are proposed.

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## ABSTRACT

Presenting many excellent material properties, unidirectional carbon fiber reinforced polymer (CFRP) has been considered as a great potential alternative to steel cables in cable structures. However, the strength and modulus perpendicular to the fiber direction of CFRP cable are significantly lower than those that are parallel to the fiber direction, which causes difficulty in anchoring CFRP cables. Therefore, anchoring is a critical problem in applying CFRP cables in cable structures. In this study, several available anchorage systems for prestressed CFRP cables are summarized in terms of design concept, anchoring mechanism and performance, and numerical simulation and mathematical methods. Although certain anchorage systems have been specially developed for prestressed concrete structures, these applications have provided meaningful experience for the development of anchorage systems for CFRP cable structures, especially the cable roofs and facades. Next, new research areas of CFRP cable anchorage systems in cable structures are introduced. Finally, the research and application status of CFRP cable structures are discussed based on three viewpoints, including CFRP cables, anchorage systems and different types of cable structures. A series of potential future research activities on anchorage systems in CFRP cable structures are suggested for promotion of the application of CFRP cables in cable structures.



**Contents**



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**Notation**

*The following symbols are used in this paper*

| | |
|---|---|
| Cof | coefficient of friction |
| $D_{bi}$ | inner diameter of barrel |
| $D_{bo}$ | outer diameter of barrel |
| $D_{wo}$ | outer diameter of wedge |
| $E$ | Young's modulus |
| $f_{sheets}$ | ultimate strength of CFRP sheets |
| $l_b$ | length of barrel |
| $l_w$ | length of wedge |
| $P$ | load |
| $P_{preset}$ | presetting load |
| $P$ | contact pressure |
| $R$ | radius |
| $t_s$ | thickness of sleeve |
| $t_{sheets}$ | thickness of CFRP sheets |
| $\Phi_{sheets}$ | material reduction factor of CFRP sheets |
| $\theta_1$ | inner slope angle of barrel |
| $\theta_2$ | outer slope angle of wedge |
| $\tau_a$ | average bond stress |
| $\tau_m$ | maximum bond stress |
| $\tau_{res}$ | residual bond stress |
| $v$ | Poisson's ratio |



## 1. Introduction

A cable structure can be defined as a structure in which a cable or a system of cables is used as a prestressed and primary load bearing structural element [1]. The cable structure is a typical representative of large-span structures, including cable bridges, cable roofs, and cable facades. Up to present, cable structures based on steel cables (hereafter referred to as steel-cable structures) have gained a widespread and successful application; however, there are two critical problems, namely the weight and metallic corrosion of steel, that impede the further development of the steel-cable structures. Therefore, to solve these problems, several engineers have made efforts to find new high-performance materials that would replace the steel cables.

Carbon fiber reinforced polymer (CFRP) is an advanced non-metallic composite material, which presents certain advantages over steel, such as higher strength, lighter weight, no corrosion, superior creep and fatigue properties, lower linear expansion coefficient and relaxation, and the ability to change the modulus of elasticity [2,3]. Thus, unidirectional CFRP possesses great potential to be made into cables to replace the steel cables in cable structures; this may considerably promote the development of cable structures [4,5]. In the past thirty years, the concept of replacing steel cables with CFRP cables directly in existing high-performance cable structures was the main research area; therefore, the development of effective anchorage systems for CFRP cables became the most important. Although several cable structures based on CFRP cables (hereafter referred to as CFRP cable structures) have been proposed, designed, researched, and even built [6–13], including cable bridges and cable roofs, the development of CFRP cable structures has not reached the initial expectations of engineers. A major reason is the lack of effective anchoring. Unidirectional pultruded CFRP tendons (such as Leadline) or strands (such as carbon fiber composite cable, CFCC) are the most commonly used types of CFRP cables. Unidirectional CFRP is a typical orthotropic material with brittleness and weak transverse mechanical properties; this creates a great challenge for anchoring CFRP cables. Several different types of anchorage systems have been designed and researched for CFRP prestressed structures, but none has yet been developed that is reliably and practically competitive compared with existing steel cable anchorage systems [14]. Therefore, a review of existing CFRP cable anchorage systems would be beneficial in terms of identifying critical problems and introducing suggestions for promotion of the development of CFRP cable anchorage systems in cable structures.

In this study, first, different types of CFRP cable anchorage systems are classified. Then, certain available anchorage systems are summarized in terms of design concept, anchoring mechanism and performance, finite element simulation and mathematical methods. Next, new research areas in CFRP cable anchorages are introduced. Finally, suggestions for the future research on anchorage systems in CFRP cable structures have been discussed and proposed.

## 2. Mechanical-type anchorages

According to the type of force that is required to balance the tension of a cable, existing CFRP cable anchorage systems can be classified into three main types, namely the mechanical-type, the bonded-type and the composite-type. The mechanical-type anchorage depends on the friction between the surface of cable and the inner surface of the component of anchorage to balance the tension of the cable. The wedge anchorage is the most