

Wedge Anchorage System for Pre-stressed CFRP Reinforcement – A Literature Review

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Abstract: Carbon Fiber Reinforced Polymer (CFRP) bars represent an excellent alternative to replace conventional steel reinforcement used in prestressed concrete. This is due to their outstanding properties such as corrosion resistant, relatively lightweight and high strength. However, the main obstacle against their wide use is the low transverse strength of the CFRP reinforcement that leads to premature failure at the anchorage zone. Consequently, it was a challenge for many researchers to modify the conventional wedge anchorage system to be used in prestressed or posttension CFRP reinforcement. This paper is a literature review that summarizes and states the main results and conclusions of previous studies conducted on the modification of wedge-type anchorage system. It gives a brief overview on the modification of the geometry of wedges and the optimum dimensions to overcome the premature failure issue. In addition, different materials used in the previous studies to get the best stress distribution at the anchorage zone are also summarized. Fatigue, short-term and long-term performance results of the modified wedge system are also presented from the literature. The overall results show a great potential to develop a wedge system that is reliable, durable and economic so that it can be used commercially. This will lead to utilize the excellent properties of CFRP in prestressed concrete industry.

Keywords: Fiber Reinforced Polymers, CFRP, wedge anchor, prestressed, posttension, concrete.

1. Introduction

Fiber reinforced polymer (FRP) shows a great potential to replace the conventional steel reinforcement in reinforced concrete industry. The main attractive features of FRP compared with steel is their corrosion resistance, high strength and light weight [1-3]. Therefore, the use of FRP reinforcement in place of conventional steel for bridge decks and other applications has been extensively studied and has proved to be a viable alternative, which has been used in many in-service structures [4-6]. It was found that carbon FRP (CFRP) tendons are well suited for prestressing applications due to their excellent mechanical properties such as high strength and low relaxation [7]. Nevertheless, the main challenge in using prestressed FRP tendons is the anchorage system. A reliable and long-term effective anchorage system is yet to be achieved. The concerns regarding the anchorage system of FRP are mainly due to the low strength in the transverse direction, brittleness of the tendon and excessive stresses at the anchorage zone. The failure modes generally take place because of the high concentrated stress, which leads to slipping (abrasive wear) or crushing of the tendon [8]. Many anchorage systems have been used for FRP prestressing or posttension applications such as expansive grouting, resin sleeve, potted resin, and clamping, spike and split wedge [9]. This paper is a literature review presenting different researches and studies conducted on the use of wedge anchorage systems for FRP reinforcement. It aims to conclude the main results and recommendations stated by the researchers in this field.

2. Mechanical Anchorage Systems for Prestressed FRP

All the anchorage systems share the same physical mechanisms but vary in methods and components. Mostly, the ultimate capacity of the FRP tendon is controlled by the anchor itself [10]. The mechanical anchorage simply uses the shear force between the FRP rod/tendon and the anchorage device to transfer the prestressing force. There are mainly two types of mechanical anchorage: clamping system and wedge system. In

the clamping anchorage system (illustrated in Figure 1 [11]), the tendon transfers the force to the anchorage through friction and shear mechanism which is affected by different factors such as roughness of the surfaces and clamping force applied by bolts. Nevertheless, the anchorage efficiency can be enhanced by introducing a low stiffness sleeve at the interface surfaces, which leads to better stress distribution on the tendon [12].

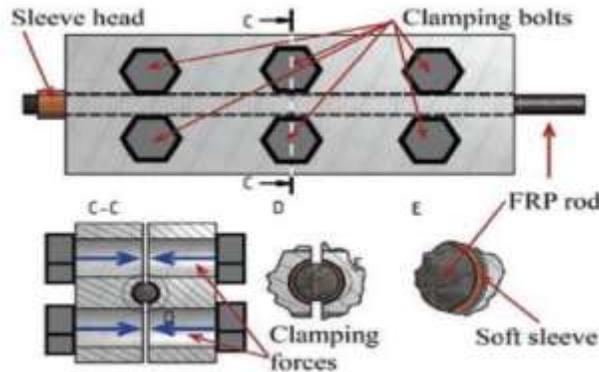


Fig. 1: Clamping anchorage [11].

The other type of mechanical anchorage is the wedge system. The wedge anchorage system is widely used since it is easy to use, reliable and reusable. However, this anchorage system consists of mainly two categories: system without any intermediate material at the tendon and wedge boundaries, and system using a sleeve to separate the tendon and wedge [12]. The wedge system is presented in details in the following sections.

3. Wedge Anchor System

This section presents the characteristics and properties of the wedge system as well as previous studies conducted to develop this system to be used in prestressed FRP tendons.

3.1. Characteristics and Components

Wedge anchorage system consists of steel wedges in a steel terminal with a conical shape at the inner surface and a cylindrical shape at the outside surface as illustrated in Figure 2. The anchorage mechanism depends on the friction between the tendon and the wedge as well as the gripping force between the wedge component and the tendon [13]. Wedge anchor is similar to those used for steel strands but longer in length and contains a low stiffness sleeve encasing the tendon to prevent notching [9]. The huge advantage of wedge anchor in pre- or post-tensioning applications is due to ease in assembly and thus it saves time and effort [11].

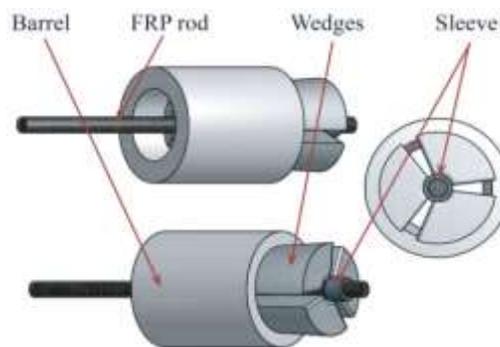


Fig. 2: Wedge anchor with inside sleeve [11].

3.2. Failure Modes

Failure modes can be divided into two main modes. The first failure mode is the failure of the anchor system such as slip of the tendon out of the anchor, slip of sleeve and tendon out of the wedge, slip of wedges out of the barrel and crushing of tendon inside the anchor. The second mode is the failure of the tendon outside the anchor thereby not involving the anchor [9]. However, FRP is an anisotropic material with low transverse strength in the normal direction of the fibers. The ratio of axial to lateral strength and stiffness of FRPs is very high (it can be as high as 30:1 in some cases) which therefore leads to premature failure of the FRP tendon at the anchorage zone as a result of excessive compressive and shear stresses as shown in Figures 3 and 4. Because of the high stiffness of the steel wedge and the transversal compression strength limitation of FRP associated with this type of anchor, the conical degree of the wedge should be very small to eliminate tendon failure [14].

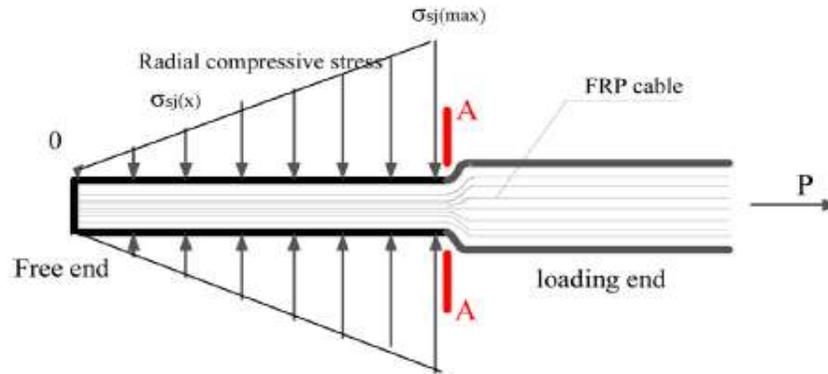


Fig. 3: Radial compressive stress on FRP rod for wedge anchor [14].

Consequently, FRP wedge system should be modified to have a minimum length of 70 mm (according to [15]) to improve the stress distribution. The target of most of previous studies is to minimize the required length of FRP wedges to be close to the conventional steel wedges given that its length is between 25-50 mm. A reliable standard anchorage system for FRP applications can be found by experimental researches covering the short and long-term behaviour of such system.

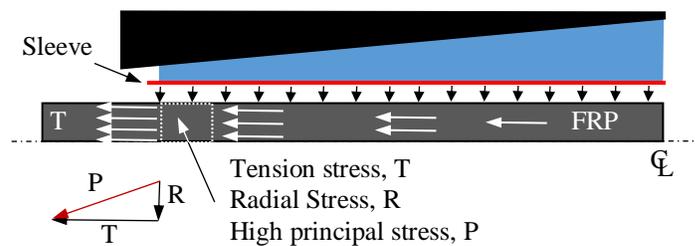


Fig. 4: Failure mode due to high principal stress at anchorage [8].

3.3 Review of Previous Studies

Nanni et al. [16] conducted a study to evaluate the short-term performance of some commercially available FRP anchorage systems for prestressed concrete. The study covered three parameters which are: mechanical performance, ease of assembly and losses at the anchor zone. Ten FRP tendons were anchored and prestressed for three days. A wedge system made of plastic without exterior lubricant or interior sand coating was tested. At a load value of 17.15 kN (26% of tendon capacity), the tendon slipped. The test was repeated with plastic wedge having sand coating and the targeted load was attained. Furthermore, aluminum wedges were found useless and all tests failed unlike steel wedges where it worked perfectly. Additionally, no effects on the prestressing of FRP were found at temperatures of -40°C and $+60^{\circ}\text{C}$. It was concluded that the wedge interior surface must be sand coated to ensure proper gripping of the tendon.

Al-Mayah et al. [17] studied the gripping mechanism of a wedge-type anchor system and the contribution of anchor components in carrying the applied load on CFRP rods. The parameters included presetting load, usage history, loading type, and sleeve material. The resultant displacements of the anchor components were measured for all test specimens. The system (illustrated in Figure 5) consists of a stainless steel barrel with four-piece wedge and aluminum or copper sleeve. Presetting load levels of 50, 65, 80, and 100 kN were used and the tests were conducted with new and reused anchors. In the majority of tests, failure of the rod occurred higher than the design load (104 kN) and no failure at anchorage were noticed. Comparison between aluminum and copper sleeves showed that aluminum performed better than copper in terms of gripping and efficiency. The load-displacement curves (Figure 6) for copper and aluminum sleeves showed how copper sleeve was poor especially in low presetting load (50 kN). Nevertheless, at 100 kN presetting load, copper and aluminum showed similar displacement values. It was stated by the authors that the copper sleeve is unreliable for use with the wedge anchor investigated in their study, unless the highest presetting loads are used. Cyclic load was also performed on the anchorage system and no effects were measured.

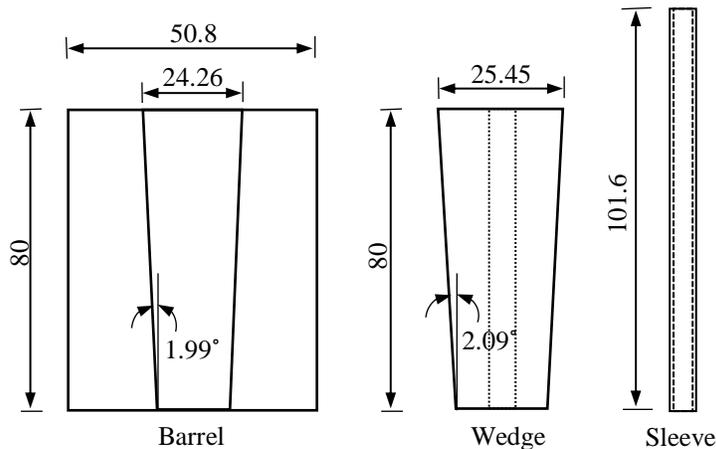


Fig. 5: Components of anchor system (dimensions in mm) [16].

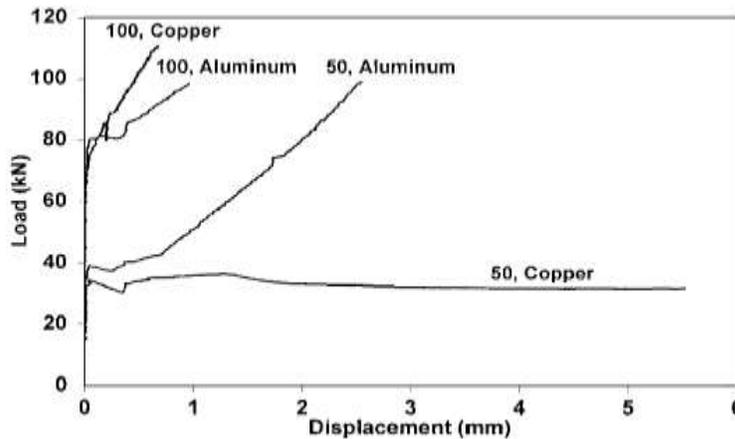


Fig. 6: Overall displacement of FRP rods using new anchor with aluminium and copper sleeves [17].

Elrefai et al. [18] tested the fatigue performance under various compensation of stresses for a wedge anchorage system developed by University of Waterloo. Fatigue tests were conducted on CFRP tendon-anchor components with minimum stress levels of 40% and 47% of the ultimate strength capacity of the tendon. Four stress ranges varying between 7% and 17% of the ultimate capacity of tendon, which represent moderate and sever condition at the tendon-anchor components were applied. The wedge system contained a steel cylinder (70 mm length and 45 mm diameter) with four steel wedges and copper sleeve. It was concluded that no premature failure occurred in the anchor and the fatigue performance satisfied the PTI (Post-Tension Institute)

requirements. The study concluded that the fatigue limit of CFRP tendon-anchor assembly should be taken as a stress range of 10% of its ultimate capacity. However, the anchorage system is expected to have an unlimited fatigue life if the stress range is below 10%. Fico et al. [19] reported that the University of Waterloo wedge system was used successfully in prestressed CFRP tendons in a bridge deck slab and no failure occurred. Besides, Sayed-Ahmed & Shrive [20] has also reported a successful tensile and fatigue performance of steel wedges with CFRP tendons.

Wedge anchorage was used for external post-tensioning of CFRP tendon by Schmidt et al. [8]. Their research aimed to examine if an anchorage can be stable at the ultimate stress level of the CFRP tendon to be post-tensioned. The anchorage system consisted of one piece wedge (length: 95 mm, largest outer diameter: 21 mm) with aluminium sleeve and a mild steel barrel (length: 105 mm, outer diameter: 30 mm), designed with an angle difference (0.1 degree) between the conical inner surface of the barrel and outer wedge surface. The conical wedge has three cuts down the longitudinal axis which shapes the integrated sleeve i.e. a gap which is a cut through the wedges shell and the slits which are stopped 1 mm short of the inside hollow. This configuration (illustrated in Figure 7) results in longitudinal and circumferential gripping, which encloses the CFRP tendon progressively during installation and tensioning of the CFRP tendon. Indents can be seen in the wedge hollow at the unloaded part of the anchorage end in order to keep the tendon particles that have been notched and sheared off when the tendon is stressed. The particles accumulate and produce volumetric expansion that decreases slipping of the CFRP tendon. The research was examining the effect of post-tensioned CFRP on flexural strength of beams. However, it concentrated on the behaviour of the anchorage system. Mild steel and aluminium anchorage exhibit elastic and plastic behaviour whereas the encased CFRP materials attribute elastic - brittle behaviour. The post-tensioning force applied ranged between 40 kN (14% of the tendon capacity) up to 140 kN (50 % of the tendon capacity). It was concluded that the anchorage was reliable and no failures were noticed.

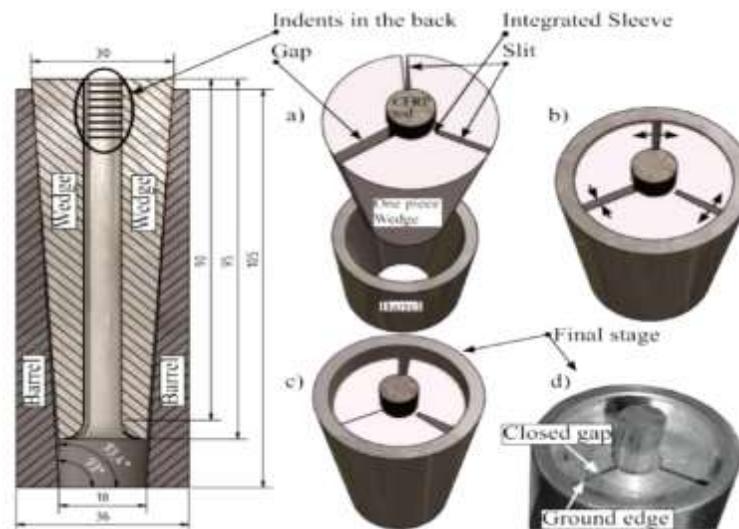


Fig. 7: Integrated sleeve-wedge anchorage geometry and installation: (a) installation of integrated sleeve wedge over CFRP rod; (b) presetting of integrated sleeve wedge; (c) and (d) preset integrated sleeve wedge [8].

One significant point mentioned by Campbell et al. [21] is the drawbacks of the metallic component of wedge system where it could be affected by corrosion. In addition, highly cost and creep issues of metallic components give rise to the use of non-metallic wedge system (shown in Figure 8). An ultra-high performance concrete was therefore used. The compressive strength of the concrete 7 days after casting exceeded 200 MPa. It was observed that seating load of 65 kN is required to reach an adequate performance of the system. Air pockets were difficult to eliminate and a series of hose clamps were used to reach the maximum adhesion with minimum air. In addition, CFRP sheets must not be exposed to ultraviolet light so that the epoxy resin will not degrade in the sheets. However, they mentioned that further studies should be conducted on the durability and creep in this anchorage system. There was no experiment conducted on this anchorage system using the ultra-high performance concrete.

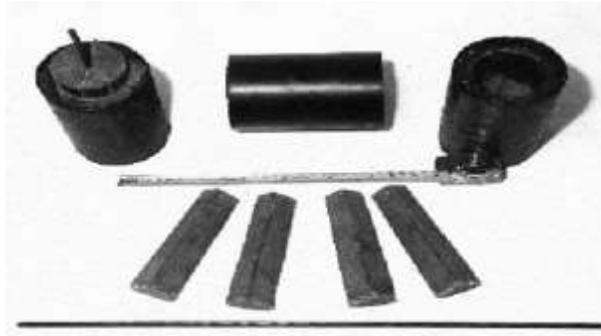


Fig. 8: The non-metallic anchorage components and assembly [21].

A finite element model of a novel anchorage system for multi-tendon FRP was developed by Wang et al. [14]. The study focused on large diameter multi-tendon BFRP (Basalt FRP) cables. They introduced a new type of conical anchor with continuous-fiber-reinforced load transfer component (LTC). The system was proposed to overcome shortcomings of conventional anchors. The four key factors affecting anchor efficiency including modulus variation, conical degree, anchor length and the thickness of LTC were analyzed respectively. In order to avoid long-term creep of resin between multi-tendons, each tendon was winded using a thin fiber roving to fill the gap between each tendon and increase their bond. In addition, gradient modulus of LTC was obtained to lower the compression and shear stresses at the loading end of the anchor (low stiffness at loading end). The LTC integrated to the BFRP bar was solidified with a specific size and conical degree via compression molding to achieve a wedge action at the anchor end. Based on the FE analysis results, different thicknesses of LTC at the loading end, including 10, 15, 20, and 25 mm were selected, whereas an optimized conical shape of 7° and an anchor length of 340 mm were fixed. The ratio of length from soft to the stiffer portion was 1: 1: 1.5: 6, and the modulus values varied from 1, 5, 15 to 25 GPa. These specifications achieved uniform axial, compressive and shear stresses as well as a correspondingly smaller LTC displacement.

Nevertheless, this study needs to be confirmed experimentally and further researches should be made to validate the given results. It is a challenge to manufacture the LTC components and it needs a special technology and thus a higher cost compared with the conventional wedge system. Besides, it needs to manufacture the LTC integrated with the FRP tendons to be used only in specific construction cases. It is observed that the length of the anchorage is too long compared with the conventional wedge system where the length is between 70 to 105 mm.

4. Summary and Conclusion

The anchorage system reviewed in this paper is the wedge-type anchorage system. As mentioned earlier, the conventional steel wedges should be modified to avoid premature failure of FRP tendon due to excessive transverse stresses at the anchorage zone. Based on this review study, the following conclusions can be drawn:

- All studies increased the length of the anchorage zone to have better stress distribution along the anchor zone. They also used different materials to replace conventional steel wedge system.
- The literature showed that almost all the modified wedge-type anchor systems were capable of handling the applied tension forces on the FRP tendon ranged between 50% to 100% of the tendon capacity. Fatigue performance of wedge system was investigated and it was revealed that no premature failure occurred in the anchorage zone during the fatigue test.
- Researchers introduced the soft metal sleeve to be used in wedge-type anchor system to distribute the compressive stress from the wedge to the tendon preventing premature failure. Aluminium sleeve showed excellent performance compared to copper one in gripping efficiency.
- A new anchorage system consists of an FRP cable with integrated wedge having different modulus between the two ends of the wedge was introduced by [14]. However, the introduced system was only presented as a finite element model and need to be tested experimentally.

The total length of the wedge anchor system ranged between 70 mm to 105 mm in most studies which are much greater than the length of the conventional steel wedge anchor systems. Therefore, further research studies are essential to optimize the length to be close to the conventional steel wedges for the ease of installation in practical field.

5. Acknowledgment

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