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Performance of Modified Wedge Anchorage System for Pre-Stressed FRP Bars

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***Abstract*—**Fiber Reinforced Polymer (FRP) is a composite material with exceptional properties that are capable to replace conventional steel reinforcement in reinforced and pre-stressed concrete structures. However, the main obstacle for their wide use in pre-stressed concrete application is the anchorage system. Due to the weakness of FRP in the transverse direction, the pre-stressing capacity of FRP bars are limited. This paper investigates the modification of the conventional wedge anchorage system to be used for stressing of FRP bars in pre-stressed applications. Epoxy adhesive material with glass FRP (GFRP) bars and conventional steel wedge were used in this paper. The GFRP bars are encased with epoxy at the anchor zone and the wedge system was used in pull-out test. The results showed a loading capacity of 47.6 kN which is 69% of the bar ultimate capacity. Additionally, nylon wedge was made with the same dimensions of the steel wedge and tested for GFRP bars without epoxy layer. The nylon wedge showed a loading capacity of 19.7 kN which is only 28.5% of the ultimate bar capacity.

***Keywords*—**Anchorage, concrete, epoxy, FRP, pre-stressed.

I. Introduction

FIBER Reinforced Polymer (FRP) composites raised as a replacement to conventional steel reinforcement in recent years. While reinforced concrete structures can be affected by corrosion especially in onshore or near shore structures, deep foundations and bridges under wet and snowy climate were de-icing salts are used, FRP is one of the best alternatives. The FRP reinforcement is a composite non-corrosive material that can replace steel reinforcement in these situations. Additionally, it has high strength coupled with lightweight which makes it an excellent replacement material for steel. It is also applicable in structures that are subjected to electrical current were the steel reinforcement cannot be used such as power generators and transformers foundations. In recent years, FRPs have been used extensively as external and internal reinforcement for concrete structures. FRP sheets are used to wrap columns to increase the loading capacity. In addition, near surface mounted FRP bars and plates have been also used to increase the flexural capacity of several structural members such as slabs and beams [1]. FRP bars have been also used as internal reinforcement in several concrete structures such as bridge decks [2]-[4], parking garages [5], [6] and reinforced concrete pavement [7].

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One of the main applications of FRP bars is their use as reinforcing bars in pre-stressed and post-tensioned concrete. Many researchers studied the possibility of using FRP in pre-stressed and post-tensioned concrete during the last decades. The main challenge in using FRP in pre-stressed concrete was the anchorage system. The concerns regarding the anchorage system is due to brittleness of FRP material and low transverse strength of FRP compared with its axial strength. The stresses are excessive at the anchorage zone which leads to several failure modes such as slipping and premature failure [8]. Therefore, a reliable and practical anchorage system needs to be developed. There are different types of anchorage systems that have been used with FRP tendons such as wedges, clamping, plug and cone resin sleeve, potted resin and expansive cement grouts [9].

All anchorage systems utilize the same physical principles but vary in mechanisms and components. In most cases, the anchor controls the ultimate capacity of pre-stressed FRP bar rather than the bar itself [10]. Mechanical anchorages simply use the frictional force between the FRP bar and the anchorage device to transfer the pre-stressing load. There are mainly two types of mechanical anchors: wedge system and clamping system. In the clamping anchorage system, the pre-stressing force applied in the bar is transferred to the anchorage through friction and shear mechanism which is affected by different factors such as clamping force applied by bolts and roughness of the surfaces [11]. The anchorage efficiency can be increased by introducing a low stiffness sleeve at the interface surfaces, which is capable of distributing the stress to the bar [12].

In this study, a steel wedge system commercially available will be modified to suit the FRP bars as pre-stressed concrete reinforcement. An epoxy layer is placed to surround the anchorage zone as an intermediate surface between the steel wedge and the FRP bar. Then, a pull-out test is performed to measure the ultimate capacity of this anchorage system. Additionally, a plastic nylon wedge is also used to substitute steel wedge. The paper is a preliminary phase of and extensive study that aims to introduce effective alternatives to overcome the anchorage problems in pre-stressed FRP bars.

II. Wedge Anchorage System

A. Characteristics and Components

Wedge anchorage system (Fig. 1) is used widely in pre-stress and post-tension reinforced concrete applications because it is very easy to assemble, cheap and saves times and effort [11]. The mechanism of wedge relays on the shear force between the bar and internal service of wedge as well as the gripping force between wedge components and the bar [13]. For FRP applications and due to the low shear strength of FRP material, the wedge anchor is modified by increasing the length and decreasing the slope angle of the wedge. In addition, a sleeve with low stiffness is set to encase the bar or tendon to prevent notching [14].

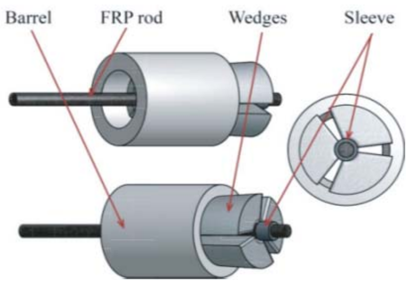

Fig. 1 Wedge anchorage system components

B. Failure Modes

The radial and shear stress at the anchorage zone are excessive which lead to several failure modes at the anchorage zone. These failure modes can be categorized in two main categories. The first failure mode is the slipping mode. In some cases, the bar and the sleeve may slip out of the wedge whereas the bar may slip out of the sleeve. The second failure mode is the premature failure of the bar inside the wedge and the failure will propagate along the bar [14]. In fact, FRP is a brittle material with low strength in the transverse direction of the fibers. The ratio of axial to lateral strength was reported to be as high as 30:1 in some cases. This will cause a premature failure at the anchorage zone before the bar reaches the ultimate capacity. These limitations associated with FRP material leads to the need to modify the conventional wedge by decreasing the conical angle and increasing the length [15].

C. Previous Studies

The wedge-type anchor, as mentioned earlier, should be modified to avoid premature failure of FRP tendon due to excessive transverse stresses at the anchorage zone. Researchers modified the dimensions of the wedge by increasing the length of the anchorage zone to have better stress distribution along the anchor zone. Furthermore, they introduce a sleeve covering the FRP tendon to prevent notching as well as reducing the transverse stresses effects on the tendon. Additionally, they used different materials to replace conventional steel wedge system. The literatures 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 [14], [16]-[20]. Fatigue performance of wedge system was also investigated by [9] and [10]. They concluded that using steel wedges with CFRP tendons they used did not result in a premature failure in the anchorage zone during the fatigue tests.

The total length of the wedge anchor system was between 70 mm to 105 mm in most of the studies [8], [10], [14], [18]. However, this length is still long and it is essential to optimize the length to be close to the conventional steel wedges for the ease of installation in practical field. The angle between the inner surface of the barrel (cylinder) and the outer surface of the wedge were recommended to be 0.1 degree or less to transfer the high transverse stress to the back of the anchorage [9], [18]-[20]. Moreover, it was found that the present of grit or sand coating in the internal surface of the wedge gives better gripping of the tendon [16]. Researchers also introduced a 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 [8].

Sleeves made of stainless steel, copper or aluminum was tested in previous studies. A study conducted by [14] compared aluminum with copper sleeve and the results showed that copper sleeve is poor in low pre-stressing loads. Nevertheless, aluminum sleeve showed excellent performance in gripping efficiency. The disadvantages of metallic components of wedge system were mentioned by [20]. These components could be affected by corrosion when used with FRP bars. One alternative material to be used in manufacturing wedge system is the ultra-high performance concrete. The compressive strength of this concrete wedge at 7 days was 200 MPa. However, the study also mentioned the difficulties of using this type of wedges such as creep and air pockets occurred in the casting molds which need to be eliminated. Furthermore, a promising anchorage system was introduced recently by [15] which are used for FRP multi-tendon cables. It consists of an FRP cable with integrated wedge having different modulus between the two ends of the wedge resulting in a better stress distribution and efficiency. The introduced system was only a finite element model and was not manufactured or tested. The integrated wedge to the FRP bar was solidified with a specific size and conical degree using a compression molding to achieve the wedge action. The optimum values from this analysis recommended a 7 degree angle for the slope of the integrated wedge and a total length of 340 mm. The modulus varies along the length of the wedge from 1 to 25 GPa with specific ratios. 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 integrated wedge with the FRP bar and it needs a special technology and thus higher costs compared with the conventional wedge system. Besides, it needs to be used only in specific construction projects. It is observed that the length of the anchorage is too long compared with other developed FRP wedge systems where the length ranges between 70 to 105 mm [8], [10], [14], [18].

III. Objectives

This paper aims to modify the commercial steel wedge anchorage system used for steel tendons in pre-stressed concrete to be suitable for FRP bars. The modifications are to achieve the best pre-stress loading capacity for GFRP bars and to minimize the stresses at the anchorage zone.

IV. Materials and Testing Procedure

The experiments conducted on an 8 mm GFRP bars manufactured by a German Company with fiber content of 73% by weight. Tensile tests were conducted on the GFRP bars and the properties were obtained and illustrated in Table I. The steel wedge (Figs. 2 and 3) is available commercially and it is used as anchor for steel tendons in pre-stressed and post-tensioned concrete. Furthermore, the epoxy layers used in this study is an adhesive material set around the bar with a length of 100 mm at the anchorage end. The thickness of the epoxy layer was 2 mm. The epoxy material specifications are presented in Table II. After setting the material around the bar, it was left to cure for one day. However, it is mentioned in the manufacturer data that the epoxy layer gain more than 80% of strength within 12 hours. The dead end of the bar was embedded in a tube filled with cement expansive grout and left to cure for two days under laboratory room temperature.

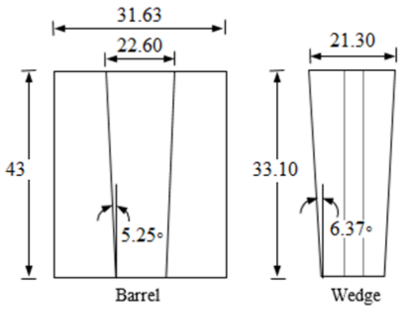

Fig. 2 Wedge dimensions in millimeters

In addition, Nylon wedge (Fig. 5) was manufactured in the laboratory and used to replace steel wedge. The dimensions of nylon wedge were exactly the same as steel wedge with internal threading. Furthermore, a nylon sleeve was also used with steel wedge and with the same dimensions of the epoxy layer. The GFRP bars are placed in the wedge as illustrated in the configuration shown in (Fig. 4). The total tested specimens were 14 specimen and the tests conducted via universal testing machine (Fig. 6). The machine was set on a rate of 0.1 mm/s.

V. Results and Discussion

Epoxy was used to absorb the excessive transverse stresses at the anchorage zone. Due to the low stiffness, it can reduce the stresses on the GFRP and transfer the load to the back of the wedge. It was found that when increasing the length of epoxy layer at the back of the wedge, the loading capacity of the anchorage system increased. First, the wedge was placed at the end of the bar and the failure load was 36.2 kN. The failure occurred at the anchorage zone when the epoxy layer crushed and the applied force were lost. However, it was realized that the wedge should be placed before the end of the bar in order to distribute the stresses smoothly to the back wedge. In the second test, wedge was placed at a distance of 35 mm before the end of the bar as shown in Fig. 4. The maximum loading capacity was found to be 47.6 kN which is about 69 % of the bar capacity. The failure mode was similar to the previous test. It was observed that displacement increased proportionally with the load increase as illustrated in (Fig. 7). The maximum displacement at the ultimate load was 2.7 mm.

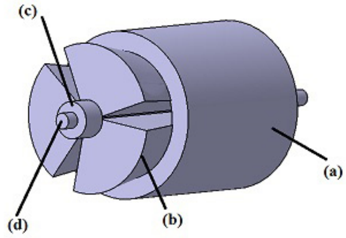

Fig. 3 Wedge anchorage system components: (a) barrel, (b) steel wedge, (c) epoxy layer, (d) GFRP bar

TABLE I
PROPERTIES OF GFRP BARS

Diameter (mm)	Cross-sectional Area (mm2)	Specific Weight (kg/m)	Fracture Strain	Tensile Strength (MPa)	Elastic Modulus (GPa)
8	50.3	0.13	0.023	1387	59.1

TABLE II
MANUFACTURER-SUPPLIED PROPERTIES OF EPOXY MATERIAL

Material	Colour	Mixed Density (kg/Liter)	Compressive Strength at 7 days (MPa)	Flexural Strength at 7 days (MPa)
Epoxy	Grey	1.58	40	20

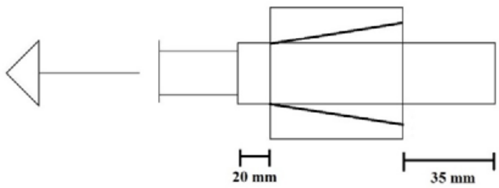

Fig. 4 Wedge and GFRP bars configuration

The concept of using nylon wedge was raised due to its low stiffness compared with steel wedge which will results in soft gripping. Nevertheless, nylon wedge performed badly when used to replace steel wedge in GFRP bars. The maximum load occurred at failure was 19.7 kN which is 28.5% of bar capacity whereas the maximum displacement was 0.48 mm (Fig. 8). Failure mode occurred in the form of slipping of wedge inside the steel barrel and after that the bar slipped out of the wedge. Due to high shear stress, the internal threading was removed by the bar. In addition, nylon sleeve was used to replace epoxy layer. The bar slipped immediately out of the nylon sleeve and no load was recorded in the data logger. There were no further tests conducted on nylon wedges. Similar results were reported by [16] where a plastic wedge was used to anchor aramid FRP bar and it produced poor performance. However, different type of plastic wedge with higher stiffness might produce better results.

Fig. 5 Steel wedge, plastic wedge and GFRP bar with epoxy layer and expansive grout at both ends

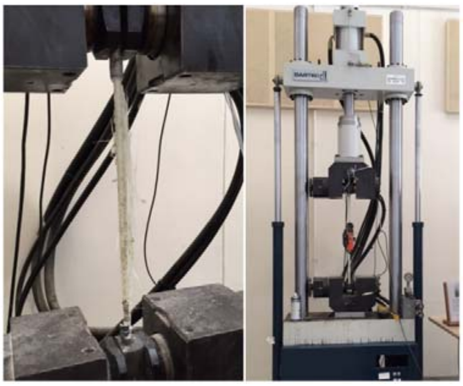

Fig. 6 Pull-out test via universal testing machine

The results of this investigation (Table III) showed a good performance of epoxy layer when used with commercial steel wedge in GFRP systems. There are many wedge systems developed by different companies especially for FRP bars However, they are expensive and not that practical due to increased length of the wedge.

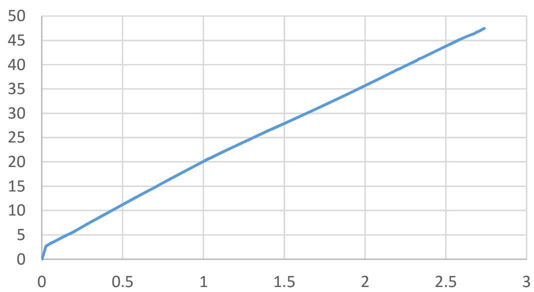

Fig. 7 Load vs. displacement curve for wedge system with epoxy layer

It was reported by [11] that FRP wedge anchorage system can only compete with normal wedge system used for steel reinforcement if the length of the wedge decreased to be with same length of regular steel wedges in the range of 25 to 50 mm. Most of the introduced FRP wedge anchorage systems designed with a length ranged between 70 to 105 mm which is not so practical especially in post-tensioned concrete. Moreover, the angle between the FRP wedge and the internal surface of the barrel should not be more than 0.1 degree which is difficult to achieve in manufacturing process [19], [20]. However, the study aimed to utilize the current steel wedge system which is cheap and available in the markets without any modifications that needs special manufacturing resulted in increased price of the system.

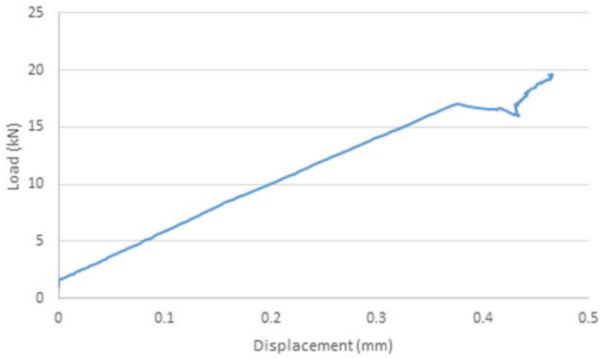

Fig. 8 load vs displacement curve for nylon wedge system

The ACI guide stated that GFRP and CFRP bars can be used in pre-stressed concrete applications where the maximum pre-stressing force should not exceed 20% and 55% of the ultimate bar capacity for GFRP and CFRP respectively [21]. Although the steel wedge with epoxy layer presented in this study could not reach the ultimate capacity of the GFRP bar, but it can provide loading capacity more than the maximum permitted pre-stressing force stated by the ACI guide. This system can be used for pre-stressed concrete to reduce deflection and give longer span slabs and beams.

TABLE III
SUMMARY OF TESTS RESULTS

	Loading capacity (kN)	Percentage from bar capacity	Strain at failure	Failure mode
Epoxy layer	47.6	69 %	0.016	Epoxy layer crushed
Plastic wedge	19.7	28.5	0.006	Bar slipped

VI. CONCLUSION

This work presents the preliminary test results of an extensive research that aims to develop a practical wedge anchorage system that can be used with FRP bars in pre-stressing and post-tension applications. In addition, different types of epoxies with better characteristics can be used. The epoxy-based adhesive materials are available in wide range of properties and it can be utilized in the same manner of this study. Furthermore, the steel wedge can be improved by increasing the length and the angle to achieve better distribution of stresses.

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