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INTERFACIAL BOND STRENGTH BETWEEN THE CIRCULAR FRP TUBE AND ITS CONCRETE

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Abstract: The interfacial bond in concrete-filled fiber-reinforced polymer (FRP) tubes (CFFT) should be sufficient to provide a full composite action between the FRP tube and its concrete core. Although, CFFT members have been widely investigated in the last two decades, there are no standards or guidelines to determine the interfacial bond strength on CFFT members. This study presents an experimental investigation of the interfacial bond strength between the circular pultruded FRP tubes and its concrete core. This research seeks also to provide a test method for determination of the interfacial bond strength of the CFFT members. Six full-scale circular CFFT specimens were tested with two different tube sizes, 305 mm diameter and 406 mm diameter, 200 mm height, and all tubes have 12.7 mm tube wall thickness. All specimens were filled by the same concrete. The specimens were tested under a test setup prepared especially for these specimens. The specimens were loaded vertically. The vertical load was applied on the concrete core while the specimen was vertically supported on the FRP tube only. The force and the slippage between the FRP tube and its concrete core were recorded to plot the interfacial bond-slip relationships for each specimen. The interfacial bond is varying from case to case according to several parameters like the concrete properties, tube thickness, tube diameter, and texture of the tube interior surface. Based on the identified parameters in the presented case, the measured interfacial bond stress was varying from 0.022 MPa to 0.028 MPa which can be neglected.

1 INTRODUCTION

In the last two decades, concrete-filled fiber reinforced polymer (FRP) tubes (CFFTs) members have been presented as a structurally-efficient competitor to replace conventional steel-reinforced concrete elements (Abouzied and Masmoudi 2015). CFFTs members have been used in several structural application namely; marine constructions, bridges, poles, and over-head sign structures. CFFT members have shown significant advantages such as permanent lightweight formwork, providing external noncorrosive reinforcement, and confining the concrete core (Ali et al. 2019). These advantages sustain their durability in the harsh environmental conditions. In addition, the concrete core confinement increases strength, stiffness, and ductility of such elements (Mohamed and Masmoudi 2010a).
Despite many researches(Abouzied and Masmoudi 2014; Mohamed and Masmoudi 2010a; b, 2007) have been conducted to investigate the axial and the flexural performance of CFFT members, extremely less concentration has been awarded to the interfacial bond performance between the FRP tube and its concrete core(Ali et al. 2017, 2019; Ali and Masmoudi 2018). In order to accomplish the CFFT structural benefits, the stress should be effectively transferred between the FRP tube and its concrete core. Practically, the interfacial bond can be achieved by depending on either shear connectors (using resin ribs) or the natural

bond between the FRP tube and the concrete (in the case of the rough texture of the interior surface of the tube).

Helmi (Helmi et al. 2005) has investigated the bond strength between the concrete core and filament-wound E-Glass/Epoxy FRP (GFRP) tube. The interior surface of Helmi's tubes had small circumferential ridges of about 0.3 mm projection and spaced at about 9 mm in the longitudinal direction. The exterior diameter of the tubes was 367 mm and the tube wall thickness was 5.7 mm. the height of the tube was 30 mm. Helmi reported that the bond strength between filament-wound GFRP tube and its concrete core equals 0.63 MPa. Nelson (Nelson et al. 2008) tested six push-through CFFT specimens embedded into reinforced concrete (RC) footings under axial compression load. The aim of their tests was determining the interfacial shear strength (bond) between the GFRP tube and concrete. Based on their experimental results for this type of tubes the average ultimate bond strength between the GFRP tube and the concrete is 0.75 MPa this value can be changed according to the surface texture, preparation of the FRP tube, concrete rupture modulus, and confining steel reinforcement in the footing. The bond-slip responses of the tested specimens have dropped to a level of about 50 to 60 percent of the ultimate bond strength when the bond reached the ultimate strength. In the Nelson's study the RC footing was the surrounding material and the tube has been pushed through the RC footing. Consequently, the interfacial bond strength in the case of the FRP tube surrounds its concrete core might be different than Nelson's tests.

Practically, the interfacial bond between the FRP tube and its concrete core is an essential parameter to evaluate the full composite action in CFFT members especially those subjected to flexure loads. Excessive slip occurs between the concrete core and the FRP tube due to lack of the interfacial bond. This slip adversely affects the composite action of the CFFT member. This paper presents experimental results of push-out tests conducted on circular CFFT specimens. The interfacial bond strength between the circular pultruded FRP tube and its concrete is investigated for two different tube diameters. No roughness has been made on the interior surface of the tube. Up-to-date, there is no standards or guidelines have been issued to test or evaluate the interfacial bond between the FRP tube and its concrete core. Therefore, this paper provides a way to test the interfacial bond(Ali et al. 2019).

2 EXPERIMENTAL PROGRAM

The experimental program reported in this paper consisted of push-out testing of six CFFT specimens. The main concept of the presented tests is to apply a vertical load on the concrete core only. On the other hand, the FRP tube was supported vertically. The load transfers by the interfacial bond from the concrete core to the FRP tube. The interfacial bond stress can be calculated as the load divided by the contact area between the FRP tube and concrete. This section describes the specimen's constituent materials, the specimen's configurations, the experimental test setup, and instrumentations.

2.1 Material Properties

Two materials have been used in this experimental program. The first material is the FRP tube while the second one is the concrete. The following points provides the characterization of the reported materials in this research.

2.1.1 FRP Tube

The FRP tubes are circular pultruded tubes. All tubes have been manufactured with electrical grade E-glass reinforcements fibers (Creative Pultrusions Inc. 2015). The tubes have been pultruded with high-performance Vinyl Ester (VE) and Polyurethane resins, VE resins are ideal for long-term performance in harsh marine environments, Polyurethane resins provide all the performance of VE resins in addition to optimal strength, toughness and impact resistance (Creative Pultrusions Inc. 2015). Two different tube diameters have been used; 305 mm and 406 mm (S-305 refer to tubes with 305mm diameter while S-406 implies tube with 406mm diameter). The tube thickness is constant for all tubes and equals 12.7mm. For each category of tubes, twelve coupon specimens were tested under axial tension and compression to determine the tubes mechanical properties on the longitudinal direction following the ASTM D3039/D3039M (ASTM D3039 2014) and ASTM D695 (ASTM D695 2010), respectively. Table 1 shows the dimensions and the mechanical properties of both tubes in the longitudinal direction, where D_o is the tube outer diameter, t_f is the tube thickness, h is the tube height , f_{cl} is the average compressive strength, f_{tl} is the average tensile strength, and E_l is the Modulus of elasticity.

2.1.2 Concrete

Ready-mixed normal weight concrete of 35 MPa target compressive strength; with aggregate size between 5-20 mm and slump of 80 ± 20 mm; was appropriated to fill the tubes. Nine cylinders and six prisms were prepared and tested on the same day of the test to determine the concrete compressive strength and the concrete modulus of rupture, respectively. The measured concrete compressive strength of the cylinders was 35 MPa ± 2 MPa and the modulus of rupture of prisms was 4.0 MPa ± 0.3 MPa.

2.2 Test Specimens

A total of six push-out specimens of two different diameters have been tested. This six specimens are divided into two groups. Each group has three identical specimens. Fabrication of the specimens started by cutting the FRP circular tubes to the required length (200 mm). Figure 1 shows a typical schematic for the specimen's details. The bottom end of the tubes has been closed by plastic sheets to avoid the leakage of the concrete water; as shown in figure 2. Afterwards, the FRP tubes have been filled with concrete.

Table 1: FRP Tube Properties

Tube ID	D_o (mm)	t_f (mm)	h (mm)	f_{cl} (MPa)	f_{tl} (MPa)	E_l (GPa)
S-305	305	12.7	200	555	665	36.5
S-406	406	12.7	200	572	711	38

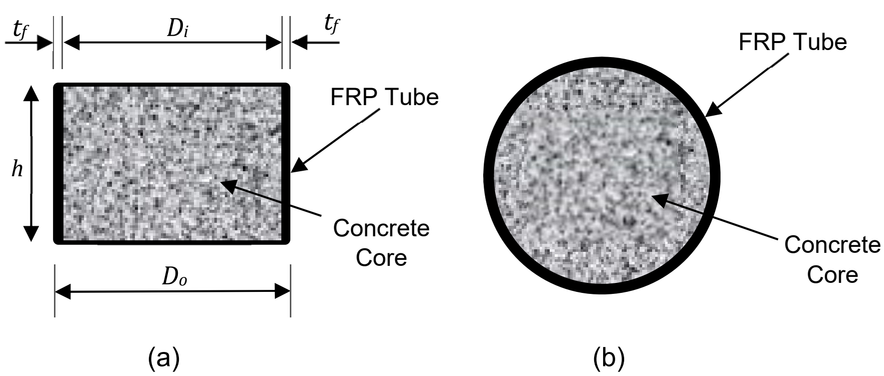


Figure 1: Schematic showing specimen details: (a) Cross-sectional elevation, (b) Cross-section view

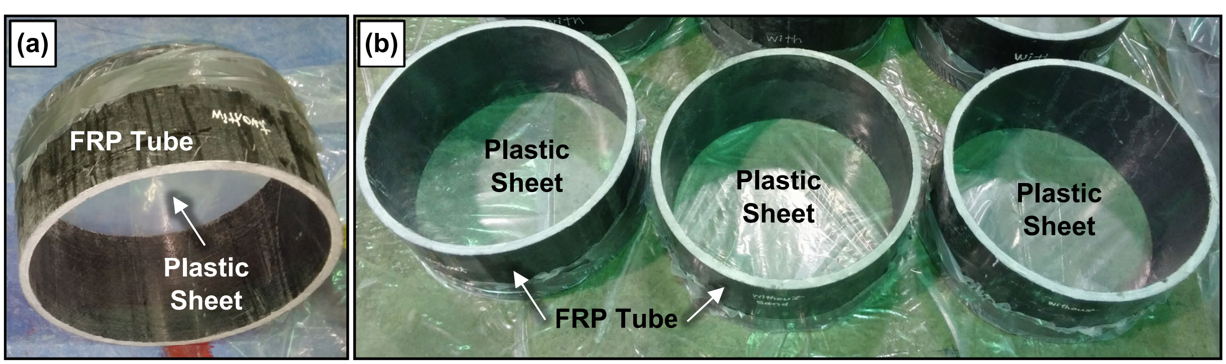


Figure 2: Preparation of specimens before casting of concrete: (a) Specimen S-305, (b) Specimen S-406

2.3 Test Setup and Instrumentations

Specimens were tested in a 60,000-pound Baldwin-Lima-Hamilton Test Machine. Specimens S-305 and S-406 were supported at the bottom on steel tube with 305 mm and 406 mm external diameter, respectively. The steel tube has been supported by three steel stiffeners; as shown in figure 3. The height of the stiffeners is higher than the steel tube by 25 mm to ensure that the FRP tube rested on the steel tube and its exterior surface is aligned with the steel tube exterior surface. The steel tubes have 6 mm wall thickness which are less than the FRP tubes wall thickness by 6.7 mm. Therefore, the concrete core can be driven downward without any obstacles. Vertical axial load (P) was applied by the machine head to the concrete core. This load is resisted by the interfacial bond between the concrete core and the FRP tube.

Two linearly variable displacement transducers (LVDTs) were used to measure the relative slip between the concrete core and the FRP tube; as shown in figure 3. The load and the LVDTs measurements have been recorded using a data acquisition system. During the testes, the data acquisition system has been programed to capture 10 reads per second.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimentally recorded load-slip responses for the tests are shown in figure 4. The captured slip value form the right LVDT was approximately identical with the value of the left LVDT. Consequently, the average slip value is used to plot all responses in this paper. Generally, all specimens demonstrated the same behavior until the ultimate load achieved then consequently the load dropped to a level of about 35% to 45% of the ultimate load. The ultimate load of the specimens has been captured at a relative-slip value located between 0.3 mm and 1 mm; as shown in figure 4. Table 2 presents a summary of the experimental results of the tested specimens. Specimens S-305-3 and S-406-1 show an ultimate load higher than the other specimen in the same size. However, their slip values at the ultimate load are approximately in the same range as the other specimens. Therefore, these two specimens have been excluded from the analysis. The interfacial bond-slip analysis has only conducted on S-305-1, S-305-2, S-406-2, and S-406-3.

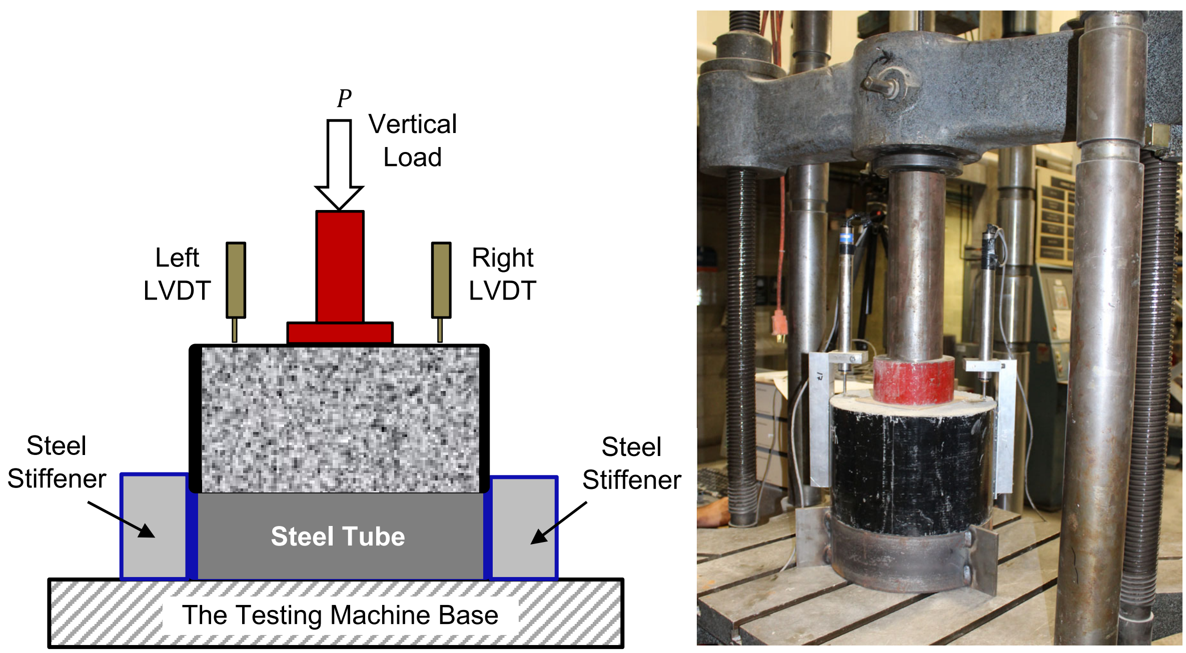
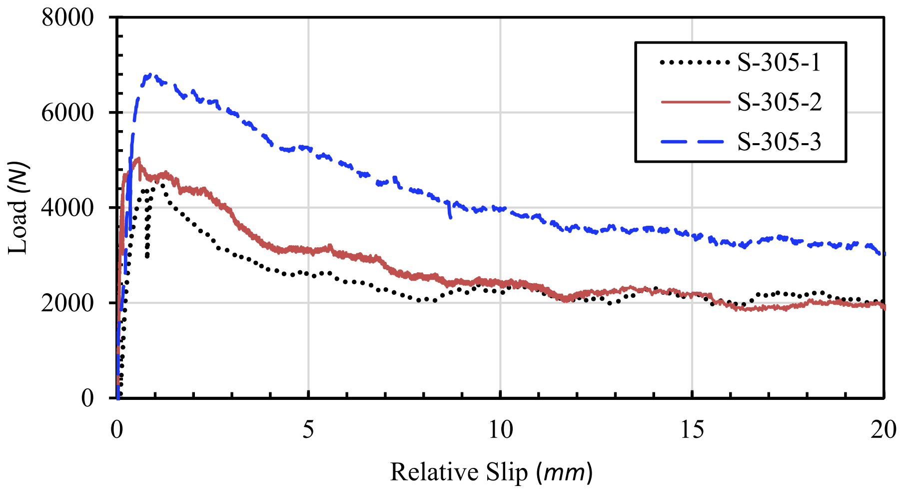
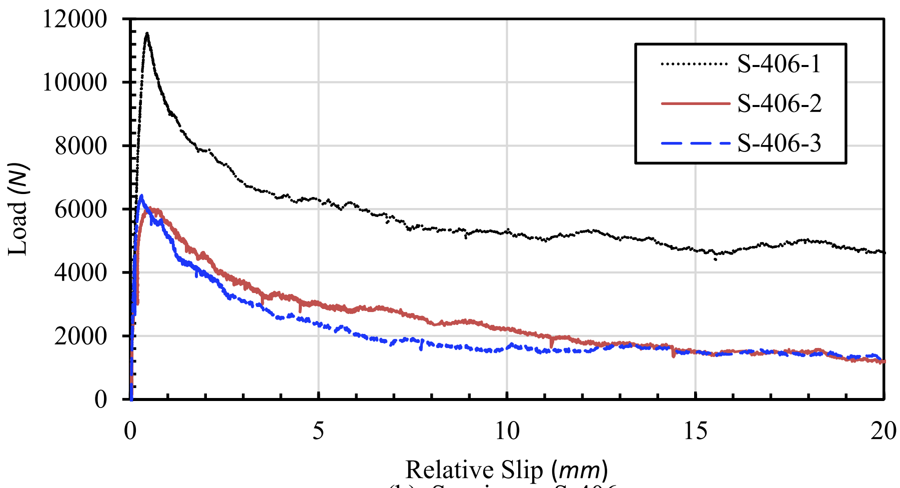


Figure 3: Typical Specimen and Method of Load Application in a 60,000-pound Baldwin-Lima-Hamilton Test Machine



(a) :Specimens S-305



(b): Specimens S-406

Figure 4: Load-relative slip relationships for the tested specimens

Table 2: Summary of Results

Tube ID	S-305-1	S-305-2	S-305-3	S-406-1	S-406-2	S-406-3
P_{max} (N)	4546	5043	6845	11565	6056	6441
δ_{ul} (mm)	1.01	0.57	0.93	0.46	0.53	0.31
τ_{max} (MPa)	0.025	0.028	0.038	0.047	0.022	0.023

Where (P_{max}) is the ultimate load, (δ_{ul}) is the average relative slip value corresponding to the ultimate load, and (τ_{max}) is the interfacial bond strength between the pultruded FRP tube and its concrete core.

The interfacial bond stress (τ) is calculated by dividing the vertical load (P) per the contact area (A_c) between the FRP tube and its concrete core. The contact area is the internal surface area of the FRP tube without the slipped surface area out the FRP tube; as shown in figure 5; where (δ) is the average relative slip value corresponding to the vertical load (P). Consequently, the interfacial bond stress at any point during the test equals the vertical load divided by the contact area, as shown in Eq.1. The interfacial bond-slip relationships of the tested specimens are shown in figure 6.

[1] $\tau = \frac{P}{A_C} = \frac{P}{\pi\, D_i\, (h-\delta)}$

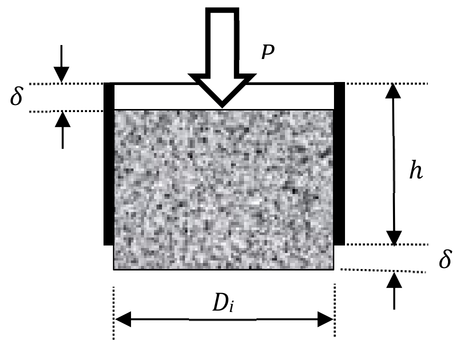
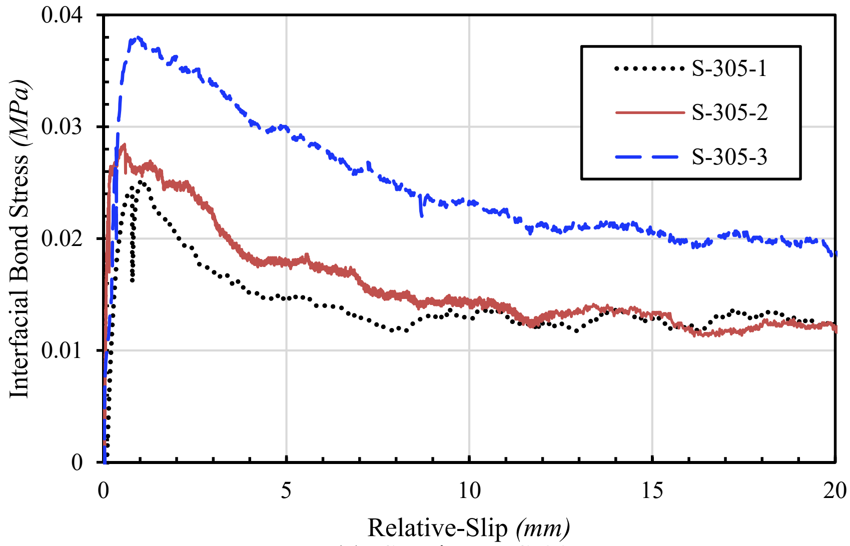
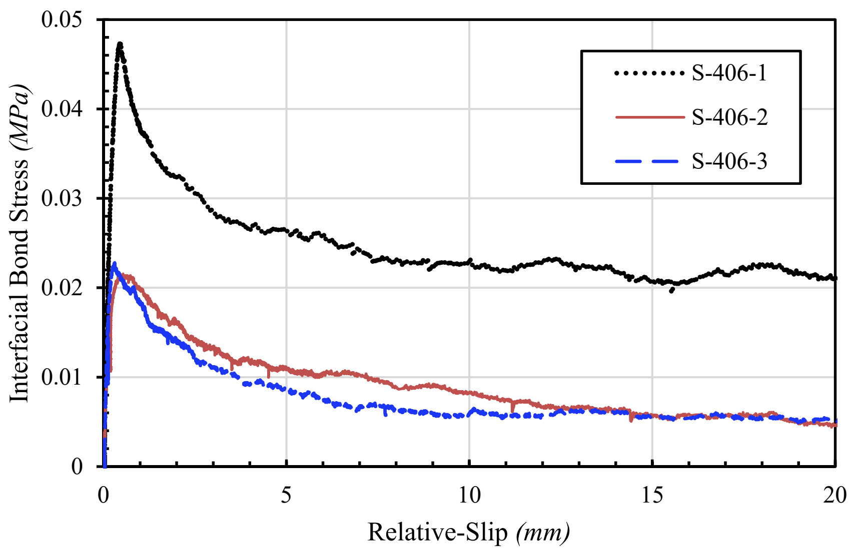


Figure 5: Schematic showing the slipping of the concrete core out the FRP tube



(a): Specimens S-305



(b): Specimens S-406

Figure 6: Interfacial bond-relative slip relationships for the tested specimens

All specimens experience an initial linear relation until the ultimate interfacial bond strength achieved. Gradual drop has been noticed after the bond stress reached the ultimate bond strength. With the excessive slip, the bond stress seems to be constant and equal to about 35% to 45% from the ultimate bond strength. After neglecting the specimens S-305-3 and S-406-1, the average interfacial bond strengths for specimens S-305 and S-406 are 0.265 MPa and 0.0225 MPa; respectively. The average bond strength of the tube with a small diameter (S-305) is higher than the bond strength of the tube with the higher diameter (S-406). Increasing the interior diameter of the FRP tube by 36% from 279.6 mm to 380.6 mm decreased the interfacial bond strength by 15 % from 0.265 MPa to 0.0225 MPa. The interfacial bond strength between the pultruded FRP tube and its concrete core is very small and can be neglected due to the very smooth texture of the internal surface of such FRP tube. The pultruded FRP tube should not use in the flexural application without using any bond-enhancer between the FRP tube and its concrete core. The shear connectors between the pultruded FRP tube and its concrete core like resin-ribs could be a method to improve the interfacial bond between the FRP tube and its concrete core. Using sand coating on the interior surface of the FRP tube could also enhance the interfacial bond between the pultruded FRP tube and its concrete core.

The reported interfacial bond strength in this paper is around 0.022 MPa to 0.028 MPa and the bond strength reported by Helmi (Helmi et al. 2005) was 0.63. This difference refers to the difference between the two types of the FRP tubes. Helm's tubes were filament-wound FRP tubes. In addition, Helm's tubes had small circumferential ridges of about 0.3 mm projection and spaced at about 9 mm in the longitudinal direction on its interior surface. This difference shows the significant impact of using shear-connector to improve the interfacial bond between the FRP tube and its concrete core.

4 CONCLUSIONS

This paper has experimentally investigated the interfacial bond between the pultruded FRP tube and its concrete core. The experimental program described in this paper is a part of the ongoing research of the authors on the effect of the interfacial bond between the pultruded circular FRP tube and its concrete core on the behavior of the CFFT member and how to improve the composite action between the tube and its concrete core. Six push-out specimens have been tested with two different tube-diameters. The main conclusions of the presented study have been written in the following points:

- The interfacial bond strength between the studied pultruded FRP tube and it concrete core is very low (0.022 MPa to 0.028 MPa) and can be neglected due to the smooth texture of the interior surface of the FRP tube.
- Increasing the FRP tube diameter reduces the interfacial bond between the FPR tube and the concrete core.
- Using concrete-filled pultruded FRP tube in structural application subjected to flexural loads should include adequate method to improve the interfacial bond strength as using shear connectors or using sand coating on the interior surface of the FRP tube.

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