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EFFECT OF TRANSVERSE/AXIAL FIBER RATIOS ON THE FLEXURAL CAPACITY OF CONCRETE-FILLED FRP TUBE BEAMS

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Abstract— **Fiber-reinforced polymer (FRP) composite materials have been used in the field of civil engineering constructions especially in corrosive environment. They can be used as internal reinforcement for beams, slabs, and pavements, or as external reinforcement for rehabilitation and strengthening different structures. One of their innovative applications is the concrete-filled FRP tubes (CFFTs) which are becoming an alternative for different structural members such as piles, columns, bridge girders, and bridge piers due to their high performance, durability and resistance to corrosion. In such integrated systems, the FRP tubes act as stay-in-place forms, protective jackets for the embedded concrete and steel, and as external reinforcement in the primary and secondary direction of the structural member [1,2,3]. This study investigates the flexural behaviour of square filament-wound FRP tubes filled with concrete, without any steel bars. The FRP tubes were fabricated by filament winding process and hand lay-up technique. Several test variables were chosen to investigate the effect of the fiber laminates structure, and the different ratios of axial-and-transverse fiber on the flexural behaviour of such CFFT beams. The beams were tested under four-point loading system. The results of the tested CFFT beams indicate significant gain in strength, stiffness, cracking moment and energy absorption with increasing the axial fiber percentage and by increasing the thickness of the FRP tube.**

Keywords— **Fiber-Reinforced Polymer, Filament Winding, Concrete-Filled FRP Tube, Beams and Flexural behaviour of beams.**

I. INTRODUCTION

Engineers and scientists are searching for innovative solutions that provide longer life and require less maintenance than conventional materials and systems. One of such innovations is concrete-filled fiber-reinforced polymer (FRP) tubes (CFFTs). The CFFTs are becoming an attractive and alternative system for many special types of structural applications especially those attacked by corrosive environments. The outer FRP tubes provide corrosion resistant elements, lateral and longitudinal reinforcement, lightweight permanent formworks, in addition to confining the inner concrete core. On the other side, the concrete core supports the tube against local buckling in addition to its role in resisting compressive loads, so, in recent years the application of concrete-filled fiber-reinforced polymer (FRP) tubes (CFFTs) has been used for different structural applications [2].

II. TEST PROGRAM

The experimental program investigates the flexural behaviour of five square CFFT beams without steel rebar, tested under a four-point bending load. This beams have same cross-section, but different in the thickness-and-the configuration of FRP tubes. All the beams were cast with low strength concrete to highlight the effect of confinement of the FRP tubes on the concrete core [7,8]. The following sections provide detailed description of the configuration of FRP tubes, test specimens, parameters, materials, instrumentation, test setup and procedures.

A. *Fabrication of GFRP Tubes and Material –*

To achieve the objectives of this study, a filament winding machine was constructed, to manufacture the light weight glass fiber-reinforced polymeric tubes (GFRP tubes). These tubes different in the thickness and configuration (or fiber laminate structure), and acts as stay-in-place forms, protective jackets for the embedded concrete and steel, and as external reinforcement in the primary and secondary direction of the structural member. The layers of tubes (or the laminate structure) consists of only two directions of fiber (0° and 90°).

FRP tubes were composed of E-glass fiber and Polyester resin. Two types of glass fiber have been used to create the layers of the tubes: (a) E-glass fiber roving, which was glued to the mandrel by the filament winding machine, as shown in Figure 1, (b) E-glass Fiber woven (or Bi-directional E-glass fiber sheet), which that contain longitudinal-and-transverse fiber in a ratio 1: 1, it was glued to the mandrel manually (or by hand layup), as shown in Figure 2. Table 1 shows the properties of fiber and the resin used based on the manufacturer data.

Five FRP tubes 1800 mm long were fabricated by filament-winding process and hand lay-up technique. All the tubes have identical square cross sections with internal dimensions of 200×200 mm2 and round corners of 25 mm radius to avoid any damage due to stress concentration at the corners [7]. This tubes different in the tube thickness, laminate structure, and the ratio of the axial-and-transverse fiber, as shown in Table 3.

Standard tests were carried out to evaluate the physical and mechanical properties of the fabricated filament-wound GFRP tubes. The most important physical properties measured were the percentage of fiber in the composite for quality issues as shown in equations 1 and 2. The fiber content (*Wf*) is the ratio of the final mass of the sample after pyrolysis (Mf) and its initial mass before pyrolysis (*Mi*). While to measure the mechanical performance of the tubes, tension tests were carried out on identical coupons to obtain the tensile strength in the axial and transverse directions. Table 2 show the configuration of tubes laminates (or stacking sequence), the tube thickness and the mechanical properties of fabricated filament-wound GFRP tubes.

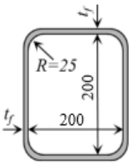
$$W_f\,(\%) = (M_f / M_i) \times 100 \qquad (1)$$

$$W_f\,(\%) = [M_i - (M_f / M_i)] \times 100 \qquad (2)$$

Table 1: Physical and mechanical properties of material

Type of Material	Physical and Mechanical Properties					
	Tensile Strength (Mpa)	Elastic Modulus (Gpa)	Fiber content %	Elongation %	Density (Kg/m3)	Curing Temp. (°c)
E-glass Fiber Roving	1117	52	70	2.5	2.54	35°c
E-glass Fiber Sheet	1500	80	60	2	3	35°c
Polyester rein	50	1.5	--	3	1170	65°c

Table 1: Physical and mechanical properties and configuration of the fabricated FRP tubes

Tube	Cross section	Stacking sequence	t_{FRP} *(mm)*	% fiber	Axial / transverse fiber ratio	Axial direction			Transverse direction		
						E_{lo} *(GPa)*	F_{lo} *(GPa)*	ε_{lo} $(*10^{-3})$	E_{tr} *(GPa)*	F_{tr} *(MPa)*	ε_{tr} $(*10^{-3})$
B1		[90°, 90°]	2	59	0	-	-	-	15.9	230	14.4
B2		[90°, sheet , 90°]	3.4	65	0.5	13.8	120	8.7	15.3	271	17.7
B3		[sheet , 90°]	2.4	62	0.67	7.8	202	25.8	13.9	288	20.7
B4		[90°, 2 sheets , 90°]	4.1	57	0.67	15.1	240	15.8	14.1	337	23.9
B5		[90°, sheet, 90° , sheet , 90°]	5.8	58	0.57	11.2	151	13.5	15.9	278	17.5

B. *Mix Proportion of Concrete and Casting –*

GFRP tubes were fixed on vertical frames and the concrete was poured into them from top end gates, as shown in Figure 4. Supporting the tubes against movement and blocking their ends were enough to start the casting process, because the tubes worked as a stay-in-place formwork. All the beams were cast with low strength concrete to highlight the effect of confinement of the FRP tubes on the concrete core [7,8]. The mix proportions for cubic meter of concrete includes 250 kg of cement, 150 litre of water, 1200 kg of limestone aggregate with a maximum size of 14 mm, 800 kg of sand. The CFFT beams were covered tightly with plastic sheets and cured for 7 days by spraying water inside the plastic sheets. At least six concrete cylinders were tested under compression machine after 28 days of casting according to ASTM C39 [4] and ASTM C469 [5]. The average unconfined compressive strength (*f'c*) was **14.5 N/mm^2**.

C. *Test specimens and parameters –*

Five CFFT beams without steel rebar, 2000 mm long and 200x200 mm^2 cross section, were fabricated by filament-winding process and hand lay-up technique for this study, this specimens different in the tube thickness and the fiber laminate structure. The objectives of this research were achieved by testing these beams under a four-point bending loads. Several test variables were considered as follows: (1)

Effect of fiber laminate structure of the GFRP tube on the flexural behaviour of CFFT beams. (2) Effect of different ratios of axial-and-transverse-fiber on the flexural performance of the filament-wound GFRP tubes filled with concrete under flexural moment.

D. Test setup and instrumentations –

The specimens were tested using a four-point bending system over a simply supported span of 1800 mm long and the distance between the applied concentrated loads was 600 mm centred with the beam length, as shown in Figure 6. These lengths give a span-to-depth ratio of 10 and shear span-to-depth ratio of 3. As such, it is believed that the beams tested in this study are governed by flexure [10]. The beams were loaded under displacement control using MTS machine with a capacity of 50 kN. Three displacement potentiometers (DPs) were used to monitor the deflection profile along the beam length. Linear variable differential transducers (LVDTs) were attached at the beams top and bottom faces of the tubes, to monitor the extreme axial compressive and tensile strains. Before test, eight axial and transverse strains gages, 10 mm long, were bonded directly on the outer tubes surfaces at their top and bottom faces, corners, and at the depth of the beam (at H/3 from the top surface). The objective of the strain gages measurements is to draw the strain profile and to record the confining action around the section. Finally, strain rosettes were located at the canter of the shear span and the mid-height to investigate the shear response of the beams. The load, deflection, and strains were recorded automatically during the tests using a data acquisition system that record the readings.

Fig. 1. Circumferential pattern of winding [90°]

Fig. 2. Stacking the fiber sheet manually
(or by hand lay-up technique)

Fig. 3. Final product of GFRP tube

Fig. 4. Casting process

Fig. 5. Tension Failure pattern on bottom flange

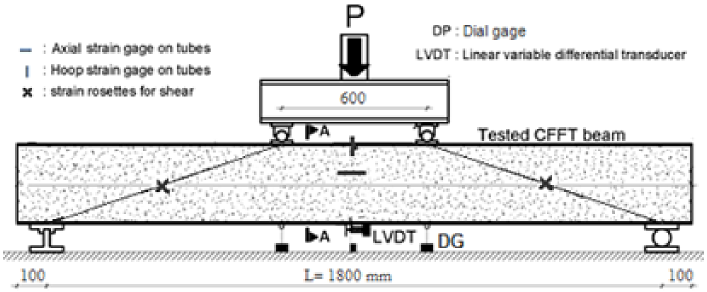


Fig. 6:
Typical schematic of test setup and instrumentations
(dimensions are in mm)

III. RESULTS AND DISCUSSION

The objectives of the following sections are to highlight the performance of the CFFT beams and study the effect of the laminate structure of FRP tubes, and increase the axial fiber percentage. Further comparisons and discussion are illustrated to study the chosen parameters on the behaviour of the CFFT beams, in the following sections.

Figure 7 shows the relationship between the moment and deflection for the tested CFFT beams. Table 3 shows details-and-results of the tested CFFT beams, including, the Stacking sequence of laminate structure of FRP tubes, cracking-and-maximum moment, initial-and-maximum stiffness, energy absorption, as well as the post cracking stiffness, which expresses the strength of the FRP tube after neglecting the resistance of the concrete section.

$$\text{post-cracking stiffness} = \frac{Vu - Vcr}{\Delta u - \Delta cr} \qquad (3)$$

Where: Vu and Vcr are the maximum-and-cracking moment, respectively. Δu and Δcr are the maximum-and-cracking deflection, respectively.

A. *Effect of Laminate Structures*

The specimens tested were divided into two types according to the laminate structure of FRP tubes. The first type includes the first beam only (B1), because it is the only beam that does not contain any fiber in the axial direction. So, it collapsed fast after the first crack, especially in the absence of reinforcing bars. The second type, includes the specimens B2, B3, B4, and B5. These specimens were made by combining the filament winding process and manual (or hand lay-up) technique. Longitudinal-and-transverse fiber were placed in these specimens by bi-directional E-glass Fiber sheet, beside winding in the circumferential pattern, as shown in Figures 1 and 2. The behaviour of these specimens was similar, and they have almost the same profile of curves, where the first part of the curves is steep, and after first crack, the stiffness decreased while the flexural resistance was increasing gradually until the maximum load that the beam could handle.

The overall behaviour of the CFFT beams is considered as bilinear, as shown in Figure 7. Before cracking, the beams start with a great flexural stiffness due to the massive gross sectional inertia. After the first crack and until maximum moment, there was a difference in the flexural stiffness among the CFFT beams, due to the different axial fiber percentage, the thickness of FRP tubes, and the different stiffness of the GFRP tubes [7]. After the first crack, the flexural stiffness decreased, because of the low modulus of elasticity of the GFRP tubes material [8]. Nevertheless, the flexural strength of the CFFT beams was increasing gradually until failure depending on the axial tensile strength of the GFRP tube [3].

B. *Effect of Transverse Fiber*

We have become certain that the maximum capacity of the CFFT beams depends mainly on the laminate structure of FRP tube, which depends mainly on the tensile strength of the bottom tube flange. To understand the effect of the lower tube flange on the maximum flexural strength, we will study the relationship between the axial-and-transverse fiber of the bottom tube flange and the maximum flexural strength of each beam.

When comparing the specimens (B2 and B3) of second group with each other, it was found that both beams are similar in the laminate structure of FRP tube, but B4 contains an additional layer of circumferential fiber, since the laminate structure for both beams respectively is [90°, sheet, 90°] and [sheet, 90°]. Consequently, both beams achieved almost close maximum strength, but the B2, that containing an extra layer of circumferential fiber, achieved a little higher flexural resistance. The maximum strength for both beams respectively is 21.3 and 19.8 KN.m, respectively, and the ratio of the maximum strength between them (B2 / B3) is 1.07.

When comparing the specimens (B4 and B5) of second group with each other, it was found that both beams are similar in the laminate structure of FRP tube, but B5 contains an additional layer of circumferential fiber, since the laminate structure for both beams respectively is [90°, 2 sheet, 90°] and [90°, sheet, 90°, sheet, 90°]. Consequently, both beams achieved almost close maximum strength, but the B5, that containing an extra layer of circumferential fiber, achieved a little higher flexural resistance. The maximum strength for both beams respectively is 32.5 and 33.9 KN.m, respectively, and the ratio of the maximum strength between them (B5 / B4) is 1.04. This is the same ratio that was between (B2 / B3) approximately, that meaning that, the additional circumferential fiber layer, had a little effect on increasing the resistance of this beam.

Although the circumferential fiber layer has little effect on increasing resistance, it has several benefits that can be summarized as follows: (1) supported the axial fiber and combine them together to resist loads. (2) Improve the stability of the CFFT beams against any undesired secondary failure like corners separation. (3) Prevent any early compression collapse that could occur on the top flange of the FRP tube beams, thus control the pattern of collapse.

C. *Effect of Longitudinal Fiber*

When comparing the specimens (B2 and B4) of second group with each other, it was found that both beams are similar in the laminate structure of FRP tube, but B4 contains an additional layer of bi-directional E-glass sheet, since the laminate structure of FRP tube for both beams respectively, is [90°, sheet, 90°] and [90°, 2 sheet, 90°], and the ratio of the distribution of axial fiber for these specimens, respectively, was (2 and 4). Consequently, B4 achieved a bending resistance one and a half times higher than B4. The maximum strength for both beams (B2 and B4) is 21.3 and 32.5 KN.m, respectively, and the ratio of the maximum strength between them (B4 / B2) is 1.5, approximately. (See Figure 7).

The same thing was repeated when comparing the specimens (B3 and B5), as B5 contains an additional layer of bi-directional E-glass sheet in the laminate structure of FRP tube, and the ratio of the distribution of axial fiber for these specimens, respectively, was (2 and 4). Consequently, B5 achieved a higher bending resistance than B3, and the ratio of the maximum strength between them (B7 / B5) is 1.7.

The previous results indicate that the axial fiber have a great effect on the maximum strength for CFFT beams, unlike the circumferential (or transverse) fiber, whose contribution to resisting loads is very small, and its main function is to prevent buckling of the axial fiber, thus control the pattern of collapse. These conclusions are confirmed by the rapid failure of B1, which does not contain any axial fiber, since the laminated structure of FRP tube for this beam is [90°, 90°], and the ultimate strength for it is 6.6 KN.m.

When studying the post-cracking stiffness values for the tested CFFT beams, it find that they depend on the ratio of the axial fiber and the thickness of the tube together. For example, when comparing the beams (B2 and B3), we find that both beams contain the same contribution of axial fiber, which is 2, but B2 that contains a tube of thickness of 3.4 mm, achieved value higher than B3 that contains a tube of thickness of 2.4 mm, since the post-cracking stiffness values for both beams (B2 and B3) are (724.9 and 651.9) N/mm2, respectively. The same thing was repeated when comparing the beams (B4 and B5), as both beams contain the same contribution of axial fiber, which is 4, but B5 that contains a tube of thickness of 5.8 mm, achieved value higher than B4 that contains a tube of thickness of 4.1 mm, since the post-cracking stiffness values for both beams (B4 and B5) are (1055.9 and 1323.3) N/mm2, respectively.

CFFT beam	Stacking sequence	FRP tube thick. (mm)	Transverse-Fiber contribution	Axial- fiber contribution	Mcr (KN.m)	Mu (KN.m)	Stiffness (KN/mm)			post-cracking stiffness (N/mm2)	Energy Absorption (KN.mm)
							Ki = Vcr/Δcr	Ku = Vu/Δu	(Ku/Ki)		
B1	[90° , 90°]	2	2	0	4.3	6.6	12.63	0.64	0.05	135.6	15.29
B2	[90° , sheet , 90°]	3.4	4	2	10.1	21.3	28.06	1.35	0.05	724.9	59.7
B3	[sheet , 90°]	2.4	3	2	6.5	19.8	9.08	0.94	0.10	651.9	75.56
B4	[90°, 2 sheet, 90°]	4.1	6	4	8.1	32.52	8.59	1.35	0.16	1055.9	141.81
B5	[90° , sheet , 90° , sheet , 90°]	5.8	7	4	7.5	33.9	15.63	1.66	0.11	1323.3	116.96

Table 3: Details-and-results of the tested CFFT beams

IV. CONCLUSIONS

1- FRP tubes act as stay-in-place forms, protective jackets for the embedded concrete and steel, and as external reinforcement in the primary and secondary direction of the structural member.

2- Concrete-filled-FRP-tube (CFFT) beams showed a considerable enhancement in the load carrying capacity and deflection.

3- The corners of the fiber reinforced polymeric tubes manufactured with filament winding technique showed high stability until the end of the tests, when no separation occurred in any of the tested beams.

4- Circumferential fiber layer has little effect on increasing resistance, but it has several benefits like, supported the axial fiber and combine them together to resist loads, improve the stability of CFFT beams against any undesired secondary failure like corners separation, and prevent any early compression collapse which could occur on the top flange of FRP tube beams, thus control the pattern of collapse.

5- Stiffness and the maximum moment of the square-CFFT beams are increases with increasing the axial fibers percentage in the laminate structure of FRP tube, as consider the axial fibers percentage a factor affecting on the maximum stiffness of the beam, especially at post-cracking stage.

6- The overall behaviour of the CFFT beams is considered as bilinear. Before cracking, the beams start with a great flexural stiffness due to the massive gross sectional inertia. After the first crack and until ultimate moment, there was a difference in the flexural stiffness among the CFFT beams, due to the different axial fibers amount (or the thickness of the tubes), and the different stiffness of the GFRP tubes. After the first crack, the flexural stiffness decreased, because of the low modulus of elasticity of the GFRP tubes material. Nevertheless, the flexural strength of the CFFT-beams was increasing gradually until failure depending on the axial tensile strength of the GFRP tube.

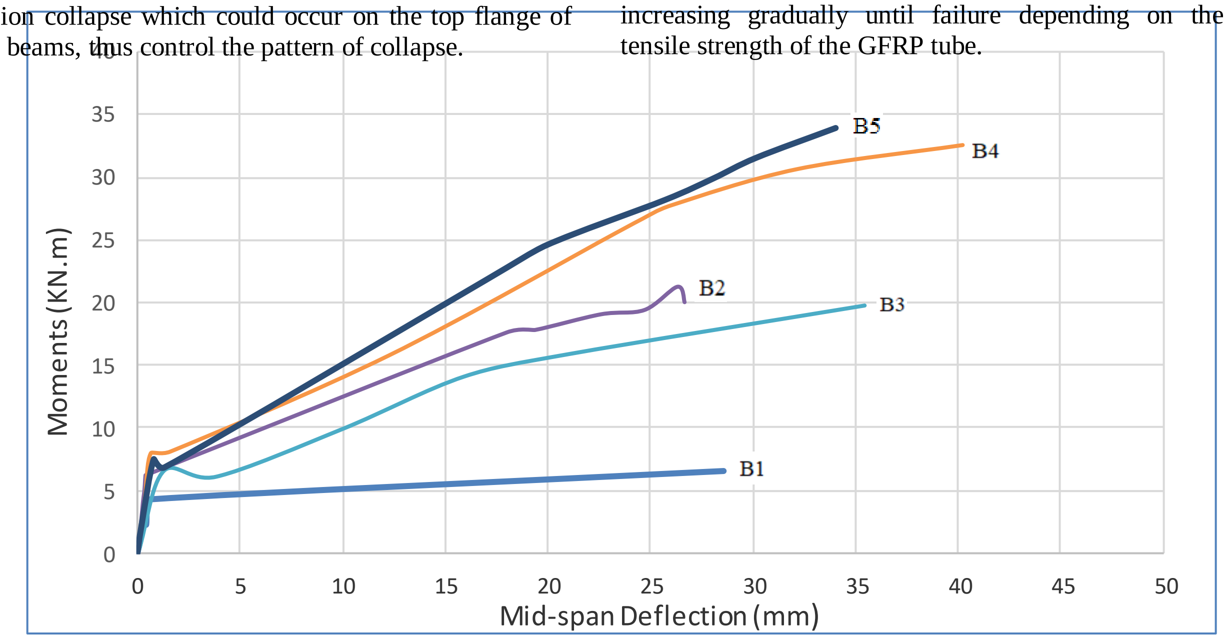


Fig. 7. Moment-deflection response of CFFT beams

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