FLEXURAL PERFORMANCE OF CONCRETE-FILLED RECTANGULAR FRP-TUBE BEAMS WITH DIFFERENT RATIOS OF TRANSVERSE TO AXIAL FIBER

Ayman Ali Dawoud [1], Ahmed Abdelaal Abdelghany [1], Ahmed Abouzied [1,2], Alaa Sherif [1]
[1] Department of Civil Engineering, Helwan University, Cairo, Egypt
[2] Department of Civil Engineering, Badr University in Cairo (BUC), Cairo, Egypt

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.

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

1 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.

Extensive research was developed on CFFTs as columns **[2]**, but comparatively limited research was carried out on CFFTs as beams **[3]**, and most of them concentrated on the circular section more than the rectangular section. However, the rectangular section has higher moment of inertia than the circular section in beams. Hence, it has higher flexural stiffness to resist the applied loads and deformations. Moreover, the construction and architectural requirements prefer the rectangular section of beams, rather than the circular beams, due to its stability during installation and its workability during connecting to other structural members like slabs and columns. The high performance of FRP composites especially the filament-wound tubes encourages researchers to use them with conventional materials like steel and concrete to produce lightweight composite sections for beams.

In most tested circular CFFT beams that failed in compression, the compression failure was predominantly governed by the compression failure of the tube flange under longitudinal compressive stresses where the tensile hoop strains (i.e., confinement effect) was insignificant **[4]**. Note that, these observations are based on flexural tests of circular CFFTs without steel reinforcement and more investigations are required to verify that observations on rectangular CFFTs.

Fam and Rizkalla (2002) **[3]** tested hollow circular GFRP tube of 100 mm diameter, B1, and compared it to another one that completely filled with concrete, B2. The results indicates that the strength and stiffness are significantly increased by filling the tube with concrete. The strength gain was 212%. The presence of concrete has contributed to the stiffness and moment resistance of the section in the compression zone of the

- *Ayman Ali Dawoud is currently pursuing masters degree program in Civil engineering at Faculty of Engineering, Mattaria Branch, Helwan University, Egypt. E-mail: eng_ayman_dawood@yahoo.com*
- *Ahmed Abdelaal Abdelghany is currently pursuing masters degree program in Civil engineering at Faculty of Engineering, Mattaria Branch, Helwan University, Egypt. E-mail ahmed.hero15@yahoo.com*
- *Ahmed Abouzied is Lecturer in Civil Engineering Department in Faculty of Engineering, Mattaria Branch, Helwan University, Egypt and Badr University in Cairo (BUC), Cairo, Egypt. E-mail: dr.a.abouzied@m-eng.helwan.edu.eg*
- *Alaa Gamal Sherif is Professor of Concrete Structures in Faculty of Engineering, Mattaria Branch, Helwan University, Egypt. E-mail: alaa_sherif@m-eng.helwan.edu.eg*

beam. The concrete also provided internal support to the tube and prevented its local buckling at the compression side. B1 failed due to local buckling and crushing of the hollow tube, while B2 had flexural tension failure due to rupture of the fibers in the tension side.

Mohamed and Masmoudi (2010) **[12]** tested six circular CFFT beams under pure pending. All beams have contained identical internal reinforcement ratio of steel or FRP bars. Two batches of concrete were used, 30 and 45 MPa, to study the effect of concrete strength on the flexural strength of CFFT beams. The results indicates that the initial and post-cracking flexural stiffness for all reinforced CFFT beams were similar, and the reinforced beams with steel bars does not have gain in the strength as compared with GFRP bars-reinforced beams. Also, The results indicates that the increase in the flexural strength for beams reinforced with GFRP bars is not significant with increasing the concrete strength strength from 30 to 45 MPa. On the other hand, the increase in the energy absorption (area under load-deflection curve) is not significant as compared with the increase in the concrete compressive strength, as it does not exceed 3% when increasing the concrete strength from 30 to 45 MPa for the beams reinforced with steel bars, and 11% for the beams reinforced with FRP bars. It can be concluded that the flexural behaviour of the six reinforced CFFT beams tested in that study were not significantly affected with increasing the concrete compressive strength from 30 to 45 MPa. Ahmed Abouzied **[1]** also studied the effect of concrete strength by varying the concrete compressive strength for the same reinforcement ratio, tube thickness, and laminate structure. Three concrete batches with compressive strength of 30, 49, and 70 MPa were studied. The results show that the concrete has insignificant effect on the flexural behaviour at the pre-yielding stage. However at the post-yielding stage, there is a minor increase in the flexural strength and stiffness with increasing the concrete strength.

Mirmiran et al. (2000) **[11]** tested circular beams with shear span to depth (a/Do) ratio of about 2, with two different reinforcement ratios (ρ) of 7.2% and 43.2%, characterized as under and over reinforced beams, respectively. The under reinforced beams consisted of symmetric ±55º glass fiber plies, while the over reinforced beams comprised of symmetric glass fiber plies with 0º and ±45º orientations, where all angles are measured with respect to the longitudinal axis of the tube. As expected, the over reinforced beams failed in compression, while the under reinforced beams failed by tensile rupture of the tube at tension side. Mohamed and Masmoudi (2010b) **[13]** tested two circular CFFTs beams, with the same diameter of 213 mm and laminate structure of 90o and ±60o, filled with the same batch of concrete, but differ in the tube thickness. One GFRP tube of Type B had thickness of 6.40 mm, which is equal to 2.2 times the thickness of the other tube of Type A with thickness of 2.90 mm. The reinforcement ratio of the tube Type B is 120% more than that of Type A. The results indicates that the beam constructed from the tube Type B experienced 33.3% higher strength than that of beam constructed from the tube Type A. At all load levels, the beam of tube Type B experienced lower deflection than that of the beam of tube Type A. Despite the increase in strength and stiffness due to increasing the thickness, the authors concluded that the increase in the flexural strength (20 to 30%) is not significant as compared to the increase in the FRP tube reinforcement ratio (120%). This is attributed to the fact that the increase in the flexural strength is mainly resulted from the contribution of the excess thickness of the FRP tubes in the tension side only. This unexpected conclusion could be attributed to that their tubes laminate structure had high angles, 90o and ±60o, which are not effective for flexural reinforcement which needs more fibers in the longitudinal direction than in hoop direction. While for axial loading the high angles is preferred for confinement process. Hence, the thickness of the tubes cannot increase the performance of the FRP tubes alone. There should be a relation between the thickness and laminate structure and type of loading (axial or bending). Ahmed Abouzied studied three thicknesses of rectangular CFFTs beams, with same reinforcement ratio and same concrete compressive strength 49 MPa. Generally, the results indicate that increasing the tube thickness increases the overall strength and stiffness of the CFFT beam. Also, the results indicate that the flexural stiffness at the pre-yielding stage was increasing with increasing the GFRP tube. At the post-yielding stage, the stiffer the GFRP tube increases significantly the flexural stiffness of the CFFT beam. The thin tube fails in tension since its axial strain at the bottom increases rapidly. The neutral axis location was moving downward with increasing the GFRP tube thickness.

2 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.

2.1 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°).

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.

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

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

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 mm^2 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.

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 show the properties of fiber and the resin used based on the manufacturer data.

Table 1: Physical and mechanical properties of material

Typ 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

2.2 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.

2.3 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.

2.4 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.

3 Failure Patterns Of CFFT Beams

All the tested CFFT beams failed under flexure without any signs of shear failure, web buckling, or slippage between the concrete core and the tubes, as shown in Figure 5. The corners of the square filament-wound FRP tubes indicated stability until the end of the tests without any separation. The stable composite action of the filament-wound FRP tubes during the test can be attributed to existence of transverse fiber that eliminates outward buckling of the axial fiber and connects strongly the tube flanges with the tube webs preventing their separation at the corners **[9]**.

4 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.

4.1 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]**.

4.2 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.

4.3 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/mm^2, 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/mm^2, respectively.

5 CONCLUSION

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 modu- lus of elasticity of the GFRP tubes material. Neverthe- less, the flexural strength of the CFFT-beams was in- creasing gradually until failure depending on the axial tensile strength of the GFRP tube.

6 REFERENCES

[1] Reinforced concrete: experimental and analytical investigations'', Elsevier–Construction and Building Materials Journal, 101: 652–660.

[2] B. Cole, A. Fam, Flexural load testing of concrete-filled FRP tubes with longitudinal steel and FRP rebar, ASCE J. Compos. Construct. 10 (2006) 161–171

[3] A. Fam, S. Rizkalla, Flexural behavior of concrete-filled fiber-reinforced polymer circular tubes, ASCE Compos. Construct. J. (2002) 123–132.

[4] American Society for Testing of Materials ASTM C469, Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression, West Conshohocken, PA, 2010.

[5] American Society for Testing of Materials ASTM D3039/D3039M, Standard test method for tensile properties of polymer matrix composite materials, West Conshohocken, PA, 2014.

[6] Ahmed Abouzied, Radhouane Masmoudi, ''Flexural behaviour of rectangular FRP-tubes filled with reinforced concrete: experimental and analytical investigations'', Elsevier–Construction and Building Materials Journal, 101: 652–660.

[7] Abouzied, A., and Masmoudi, R. (2014). "Flexural behaviour of new partially concrete-filled filament-wound rectangular FRP tube beams". Proceedings of 4th International Structural Specialty Conference CSCE2014, Halifax, NS, May 2014, CST-171:1-10.

[8] Abouzied, A., and Masmoudi, R. (2015). "New design of rectangular partially concrete-filled filament-wound FRP tube beam". Proceedings of 3rd conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures SMAR 2015, Antalya, Turkey, September 2015.

[9] Belzer, B., Robinson, M., and Fick, D. (2013). "Composite action of concrete-filled rectangular GFRP tubes". ASCE Composites for Construction Journal, 17(5): 722-731.

[10] B. Cole, A. Fam, Flexural load testing of concrete-filled FRP tubes with longitudinal steel and FRP rebar, ASCE J. Compos. Construct. 10 (2006) 161– 171.

[11] Mirmiran et al. 1998, 2001; Fam and Rizkalla 2001; Lam and Teng 2003, 2004; Hong and Kim 2004; Zhu at al. 2006; Teng et al. 2007; Ozbakkaloglu and Oehlers 2008a, 2008b; Mohamed and Masmoudi 2008a, 2008b, 2010a; Mohamed et al. 2010; Park et al. 2011; Abouzied et al. 2012b; Abouzied and Masmoudi 2012, 2013; Ozbakkaloglu 2013a, 2013b; Vincent and Ozbakkaloglu 2013; Idris and Ozbakkaloglu 2013; Riad Benzaid and Habib-Abdelhak Mesbah; Sahear Y. Ghanem 2016; Xuxu Wang and Yujun Qi and Yunlou Sun and Zhijin Xie and Weiqing Liu 2019; and others.

[12] Mohamed, H., and Masmoudi, R. (2010a). "Axial load capacity of reinforced concrete- filled FRP tubes columns: experimental versus theoretical predictions". ASCE Composites for Construction Journal, 14(2): 1-13.

[13] Mohamed, H., and Masmoudi, R. (2010b). "Flexural strength and behaviour of steel and FRP-reinforced concrete-filled FRP tube beams". Elsevier Journal of Engineering Structures, 32: 3789-3800.

Table 2: Physical and mechanical properties and configuration of the fabricated FRP tubes

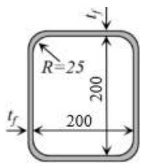
Tube	Cross section	Stacking sequence	t_{FRP} (mm)	% fiber	Axial / transverse fiber ratio	Axial direction E_{lo} (GPa)	Axial direction F_{lo} (GPa)	Axial direction ε_{lo} ($*10^{-3}$)	Transverse direction E_{tr} (GPa)	Transverse direction F_{tr} (MPa)	Transverse direction ε_{tr} ($*10^{-3}$)
B1		[90°, 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

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

CFFT beam	Stacking sequence	FRP tube thick. (mm)	Transverse-Fiber contribution	Axial- fiber contribution	Mcr (KN.m)	Mu (KN.m)	Stiffness (KN/mm) Ki = Vcr/Δcr	Stiffness (KN/mm) Ku = Vu/Δu	Stiffness (KN/mm) (Ku/Ki)	post-cracking stiffness N/mm2)	Energy Absorption (KN.mm)
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

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

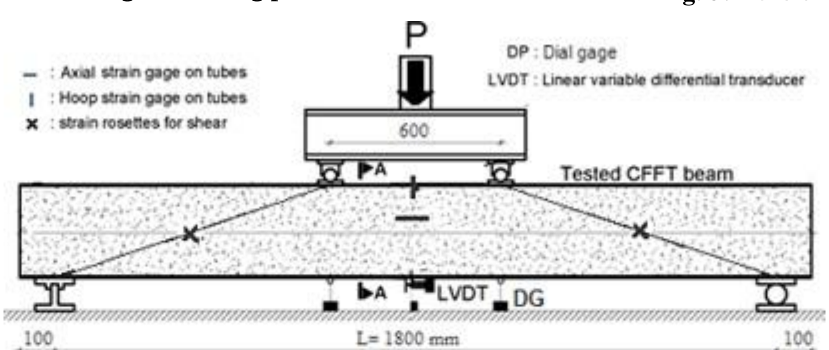


Fig. 6: Typical schematic of test setup and instrumentations (dimensions are in mm)

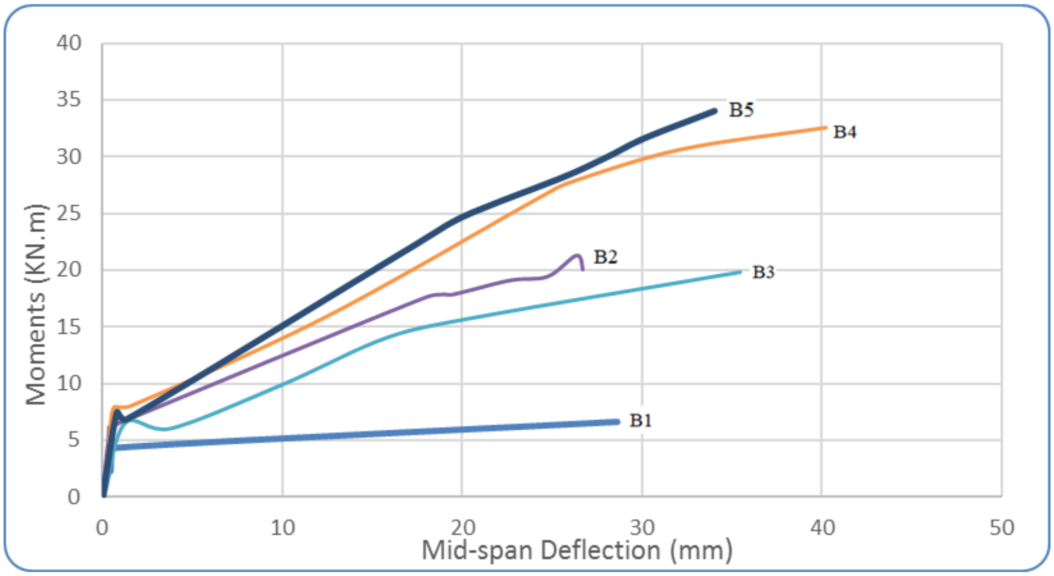


Fig. 7: Moment-Deflection Response of CFFT beams