New design of rectangular partially concrete-filled filament-wound FRP tube beam

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ABSTRACT: This research introduces a new design of a rectangular fiber reinforced polymer (FRP) tube beam partially filled with concrete. The beam contains an outer rectangular FRP tube with an inner hollow circular FRP tube shifted toward the tension zone. The space between the tubes is filled with concrete. Steel bars at the tension side were provided to enhance the stiffness and serviceability of the composite section. The FRP tubes are manufactured by filament-winding process using E-class glass fibers and vinyl-ester resin. The flexural behavior of the partially concrete-filled FRP tube (CFFT) beam was compared with a fully CFFT beam and another conventional reinforced concrete (RC) beam having identical dimensions and flexural steel reinforcement. The results showed that the new design of partially CFFT beam exceeds by far the performance of conventional RC, in terms of strength to weight ratio, ductility, and failure propagation, in addition to its high durability. The partially CFFT flexural strength was 141% more than the conventional RC beam strength, while its weight is 30% lighter than the RC beam, achieving a 246% enhancement in strength-to-weight ratio. Moreover, the partially CFFT beam flexural strength was 6% more than the fully CFFT beam, achieving an enhancement in strength-to-weight ratio by 52%.

1 INTRODUCTION

Concrete-filled fiber reinforced polymer (FRP) tubes (CFFTs) are becoming an attractive alternative structural system for many special types of structural applications, especially those attacked by corrosive environments. A lot of research was carried out on CFFTs as columns, but limited research was carried out on CFFTs as beams (Mohamed and Masmoudi (2010)) specifically those with rectangular section. The rectangular section is more rigid and stiff, than the conventional circular CFFT, which leads to gain more flexural strength and to resist high deformations. In fully CFFT beams, the concrete core is cracked and slightly contributes to bending resistance especially in the circular section where the compressed concrete is limited above the neutral axis. As such, the concrete below the neutral axis represents an excess dead weight, and consequently a higher cost of construction and wasteful resources.

A number of FRP-concrete hybrid systems have been developed over the years, including both open and closed FRP forms, to reduce the excess weight of cracked concrete below neutral axis as Deskovic and Trinatafillou (1995), Canning et al. (1999), Chakrapan (2005), and Khennane (2009). Fam and Rizkalla (2002) investigated the flexural strength of circular CFFT beams with inner holes. One of the holes configurations was maintained by an eccentric hollow glass-FRP (GFRP) tube shifted toward the tension zone. This configuration increased the flexural strength by 39% compared to the fully CFFT beam. Fam et al. (2005) designed a rectangular section of filament-wound FRP tube with an inner air void. The strength of the voided section reached 78% of that completely filled with concrete, and failed by inward buckling and fracture of the concrete flange at the compression side.

This research introduces a new design of rectangular CFFT beam with an inner hollow circular FRP tube shifted toward the tension zone to act as flexural reinforcement and to support the concrete core at the compression zone. Also the section was reinforced with steel bars at the tension side to enhance the stiffness and serviceability of the beam. The outer tube provides flexural and shear reinforcement, and protection against corrosion, in addition to being a stay-in-place formwork. The new voided section was compared with a fully CFFT beam and another conventional (RC) beam to evaluate its flexural behavior.

2 EXPERIMENTAL PROGRAM

Three types of full-scale rectangular beams were tested under four-points bending loads and compared together; conventional RC beam, fully-CFFT beam, and partially-CFFT beam. The following sections provide a detailed description of the experimental program.

2.1 GFRP tubes

Two different sizes of GFRP tubes were fabricated by the filament-winding process, as shown in Figure 1, and composed of E-glass fibers and vinyl-ester resin. The first size is a rectangular tube, 305×406 mm with round corners of 25 mm radius, as an outer tube. The second size is a circular tube, 218 mm diameter, as an inner tube. The fibers oriented at 90^o and $\pm30^o$ with respect to the longitudinal axis of the tube as shown in Figure 1. The helical pattern [$\pm30^o$] was used to provide flexural rigidity in the longitudinal direction of the beam, while the circumferential pattern [90^o] was used to provide shear reinforcement, confinement, and to prevent buckling of the inclined fibers. The fiber volume fraction was 62% and 75% for the rectangular and circular tubes respectively. After curing, tests were developed to evaluate the physical and mechanical properties of the filament-wound tubes. For the rectangular tube, five coupons in each direction were tested under tension according to the standard test method ASTM D3039/D3039M (2014), and another five coupons in each direction were tested under compression according to ASTM D695 (2010). While for the inner circular tube, the tension and compression tests were carried out only in the longitudinal direction. Table 1 lists the details of the GFRP tubes. Before casting, the tubes' surfaces which would be adjacent to the concrete were roughened by a layer of vinyl-ester resin and coarse sand to enhance the bond beneath.

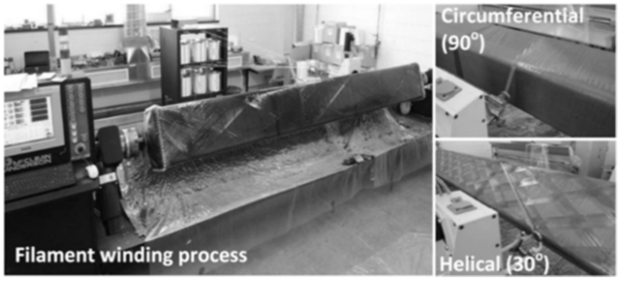

Figure 1. Filament winding process

Table 1. GFRP tubes configurations and mechanical properties

Tube ID	Cross section (mm)	Stacking sequence	% Fibers	t_{frp} (mm)	Mechanical properties	Long. direction			Transverse direction		
						E_{lo} (GPa)	f_{lo} (MPa)	ε_{lo} (mm/m)	E_{tr} (GPa)	f_{tr} (MPa)	ε_{tr} (mm/m)
$OR2_{30}$	Rec. 305×406	[90°, ±30°, 90°]	62	3.4	Ten. test	17	170	14.3	16	243	19.9
					Comp. test	13	-88	-6.7	17	-172	-10.5
$IC4_{30}$	Cir. Ø = 218	[90°,±30°, ±30°,90°]	75	3.1	Ten. test	17	213	16.7	---	---	---
					Comp. test	20	-130	-7.0	---	---	---

2.2 Beam specimens

Three beam specimens, 3.2 m long and 305×406 mm cross section, were prepared for the current paper (see Table 2). The first beam is a conventional RC beam reinforced with 4Φ15M as flexural steel reinforcement at the bottom, 2Φ10M as top steel reinforcement, and steel ties Φ10M@150 mm as shear reinforcement, noting that the steel yield strength is 419 MPa. The second beam is a fully-CFFT beam ($OR2_{30}$) reinforced with 4Φ15M at the bottom. The third beam is a partially-CFFT beam ($OR2_{30}$-$IC4_{30}$) which has identical outer GFRP tube and bottom reinforcement as $OR2_{30}$, but it has an inner hollow circular GFRP tube shifted toward the tension zone. The length of the inner GFRP tube is, 2.9 m, shorter than the outer tube for casting and reinforcing purposes. The ends of the hollow part were shifted axially for a certain length inside the circular tube to keep a solid part at the supports to prevent any local failure or web buckling at this region during the test. All the beams were casted with the same concrete patch. The average unconfined compressive strength at 28 days was 49 MPa. The RC beam was casted horizontally in a wooden box formwork, while an inclined strong frame was used to simplify pouring concrete from the top end gate as shown in Figure 2(b).

2.3 Test setup and instrumentations

The beam specimens were tested under a four-points bending load setup as shown in the schematic in Figure 3. The beams are 3.20 m long. The clear span between the supports is 2.92 m and the distance between the applied concentrated loads is 0.72 m centered with the beam. The beams were loaded under displacement control with a constant rate of 1 mm/min using MTS machine with a capacity of 10000 kN. Three displacement potentiometers (LVDTs) were used to measure the deflection profile along the beam length. Another two displacement potentiometers were located at the ends of the beam to measure any relative displacement (slip) between the concrete core and the tube. Electrical strain gages were attached to the reinforcing bars, concrete surface and GFRP tubes surfaces at the most critical section (at mid-span). The load, deflection, and strains were recorded during the test using a data acquisition system.

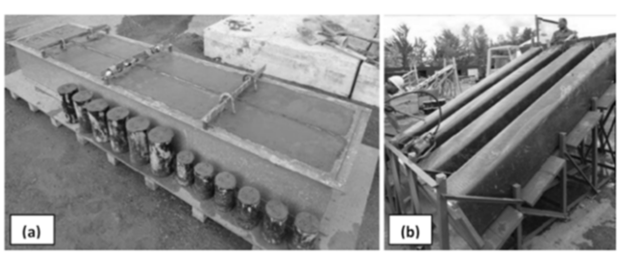

Figure 2. Casting process: (a) for RC beams, (b) for CFFT beams

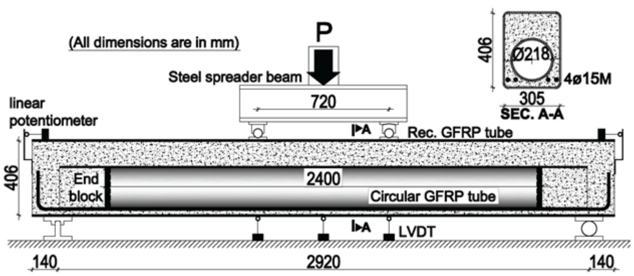

Figure 3. Schematic of test setup

Table 2. Beam specimens and summary of test results

Beam ID	Out. tube	In. tube	Bot. steel	Top steel	Steel ties	f'_c (MPa)	Load P (kN)			Δ_u (mm)	Ductility (kN.m)	Failure mode
							Crack	Yield	Peak			
RC Reference	---	---	4Φ15	2Φ10	Φ10/ 150mm		49	213	237	29	5	Tension
$OR2_{30}$ Fully-CFFT	$OR2_{30}$	---	4Φ15	---	---	49	90	274	485	72	26	Tension
$OR2_{30}$-$IC4_{30}$ Partially-CFFT	$OR2_{30}$	$IC4_{30}$	4Φ15	---	---		78	326	513	57	22	Comp.

f'_c is the unconfined compressive strength of concrete. Δ_u is the ultimate deflection at peak load.

3 RESULTS AND ANALYSIS

Table 2 presents a summary of the beam test results such as; the load at first crack of concrete, the load at yielding of the embedded steel reinforcement, the maximum capacity (peak) of the beam, the ultimate mid-span deflection at the peak, the ductility in term of the energy absorption determined by the area under the load-deflection curve until the peak, and the failure mode. No slip between the concrete core and the tubes was recorded until the ultimate capacity of the beams, even after failure the maximum slip measured did not exceed 0.04 mm. That attributed to the roughened surface of the tubes, and the existing of the deformed steel bars, with end legs, that hold the concrete core in its place. The following sections provide comparisons and discussions for the test results through presenting the load-deflection responses (Figure 3) and failure patterns of the rectangular CFFT beams (Figure 4), and the strength-to-weight ratio.

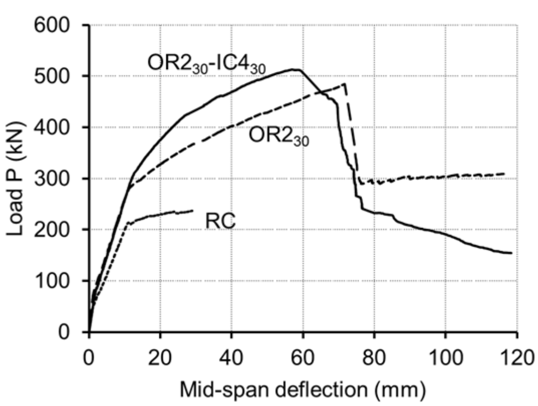

Figure 3. Load-deflection response

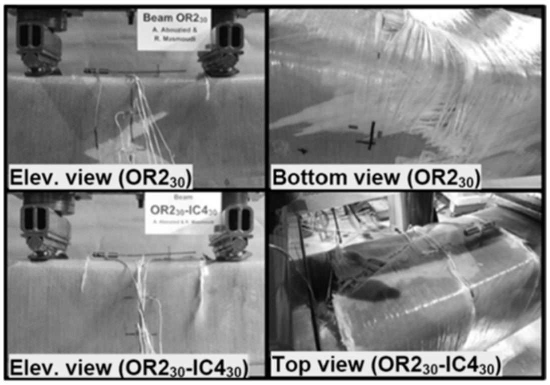

Figure 4. Failure pattern of CFFT beams

3.1 Load-deflection response

Table 2 and Figure 3 show the superior gain in strength, stiffness, and ductility of the rectangular CFFT beams compared to the conventional RC beam.

3.1.1 Conventional RC beam

The conventional RC beam failed in tension with vertical flexural cracks at the pure moment zone and no diagonal cracks at the shear zone were noticed. The first crack happened at a load 49 kN. Then the slope of the curve changed, due to changing from the gross behavior to the cracked behavior, with almost a linear behavior until reaching the yielding of the bottom steel reinforcement, which happened at a load 213 kN. After yielding, the stiffness of the beam was almost dissipated resulting in a yielding plateau due to the plastic hardening of the steel. The concrete at the top failed in compression when it reached its maximum compressive strain (0.0035) at a load 237 kN and a mid-span deflection 29 mm. The yielding load will be used to describe the RC beam capacity in comparison with other beams.

3.1.2 Fully-CFFT beam (OR2$_{30}$)

The fully-CFFT beam (OR2$_{30}$) behaved significantly stiffer and stronger than the RC beam. The overall behavior can be considered as bi-linear. The first crack happened at a load 90 kN, which is 83% greater than that of the RC beam. It is attributed to adding the GFRP tube thickness to the section reinforcement, in addition that the roughened surface delayed the generation of the cracks. After that, a semi linear behavior was noticed until reaching the yielding of the embedded reinforcement steel at a load 274 kN, which is 29% greater than that of the RC beam, because the GFRP tube behaved as an additional reinforcement in the cracked section. Since the yielded steel loses almost its high elasticity modulus, the cracked section inertia and subsequently the flexural stiffness decrease. This is indicated by the changeable slope of the load-deflection curve after yielding. Nevertheless, the strength of the fully-CFFT beam increased gradually until failure. During this stage, the section was being balanced under tension forces from the GFRP tube below neutral axis, and compression forces from the concrete and the tube above the neutral axis. Finally, the failure happened at the tension side with a sudden loss of strength and an axial rupture of fibers as shown in the bottom view of OR2$_{30}$ in Figure 4. The linear behavior of the load-deflection curve after yielding and the final tension failure confirm that the strength of the fully-CFFT beam was governed by the GFRP tube, at tension side, which is considered as an elastic material. The maximum capacity of OR2$_{30}$ beam was 485 kN, which is 128% greater than the capacity of the conventional RC beam. After failure, there was a residual strength, shown by a horizontal plateau, because of the plastic hardening of the yielded steel bars. This is a positive point of such hybrid composite section. All previous notations indicate the outstanding performance of this type of hybrid rectangular CFFT beam.

3.1.3 Partially-CFFT beam ($OR2_{30}$-$IC4_{30}$)

An enhancement in the behavior of the partially-CFFT beam ($OR2_{30}$-$IC4_{30}$) was pronounced compared to the conventional RC beam and the fully-CFFT beam. The overall behavior is considered as multi-linear. The first crack happened at a load 78 kN, which is 58% greater than that of the RC beam due to adding the inner and outer GFRP tubes thicknesses to the section reinforcement, and the roughened surface delayed the generation of the cracks. While, the first cracking load of the partially-CFFT beam is 14% lower than that of the fully-CFFT beam ($OR2_{30}$). It is attributed to removing the concrete-mass area, by the void, from the gross section. After cracking, $OR2_{30}$ and $OR2_{30}$-$IC4_{30}$ had almost the same initial flexural stiffness until yielding of bottom steel reinforcement. The yielding load of $OR2_{30}$-$IC4_{30}$ happened at a load 326 kN, which is 53% and 19% greater than that of the RC beam and $OR2_{30}$, respectively, because the outer and inner GFRP tubes acted as a flexural reinforcement. After yielding, $OR2_{30}$-$IC4_{30}$ behaved stiffer than the fully-CFFT beam $OR2_{30}$ in a non-linear way until failure. During this stage, the section was being balanced under tension forces from the inner and outer tubes below neutral axis, and compression forces from the concrete and the tube above the neutral axis. The non-linear behavior of the load-deflection curve after yielding and the final compression failure of the beam confirm that the strength of the partially-CFFT beam was governed by the confined concrete which is considered as a non-linear material. The failure happened at the compression side by an outward buckling followed by a transverse rupture of fibers at the tube top flange as shown in the top view of $OR2_{30}$-$IC4_{30}$ at Figure 4. This kind of failure means that the concrete at the compression zone was effectively confined by an active confining action by the inner tube and a passive confining action by the outer tube. As a result of confining the concrete at the compression zone and increasing the reinforcement ratio conducted by the inner tube at the tension zone, the maximum capacity of the voided CFFT beam was 513 kN, which is 141% and 6% more than the capacity of the RC beam and the fully-CFFT beam, respectively.

The ductility of the partially-CFFT beam is significantly greater than the ductility of the RC beam, and relatively close to the ductility of the fully-CFFT beam as listed in Table 2. However the partially-CFFT beam failed in compression, the ultimate failure was ductile (not brittle). It can be concluded that, the ductility (deformability) level is controlled by the amount of each following component and the interaction between them: 1) the concrete area in the compression zone, 2) the steel reinforcement ratio, 3) the sectional area of the inner FRP tube, and 4) the sectional area of the outer FRP tube.

3.2 Strength-to-weight ratio

The weight of the partially-CFFT beam ($OR2_{30}$-$IC4_{30}$) is about 70% the weight of the fully-CFFT beam ($OR2_{30}$) and the RC beam. The flexural strength of the partially-CFFT beam is 513 kN, while the flexural strength of the fully-CFFT beam and the RC beam is 485 kN and 213 kN, respectively. By dividing the strength by the weight factor, considering the weight of the fully beam as a unit, the new strength of the partially-CFFT beam is 736 kN, while the strength of the fully-CFFT beam and the RC beam remains constant. Thus, the strength-to-weight ratio of $OR2_{30}$-$IC4_{30}$ is 52% and 246% higher than those of $OR2_{30}$ and RC beams, respectively. Based on the results in this paper a durable lightweight CFFT beam system with a high-performance has been introduced. This system could replace efficiently the heavy fully-CFFTs, subsequently reduce the cost of transportation and installation in addition to the dead weight of structures.

4 CONCLUSIONS

An experimental investigation on a new design of a rectangular partially concrete-filled FRP tube (CFFT) beam has been conducted in this paper. The main concluded points are:

1) The CFFT system is quite simple as the tube provides a permanent formwork in addition to act as flexural and shear reinforcement.
2) The rectangular CFFT beams experienced higher ductility, higher stiffness, and superior strength than the conventional RC beams.
3) The flexural strength of rectangular fully-and-partially-CFFT beams are 128% and 141%, respectively, higher than the conventional RC beam strength.
4) The rectangular partially-CFFT beam weighs 70% the RC beam, while its flexural strength is 141% more achieving an overall strength-to-weight ratio 246% higher.
5) The rectangular partially-CFFT beam weighs 70% the rectangular fully-CFFT beam, while its flexural strength is 6% more achieving an overall strength-to-weight ratio 52% higher.
6) The load-deflection behavior of the rectangular CFFT beam is non-linear.
7) The fully-CFFT beam failed by an aggressive axial rupture of fibers at the tension side, while the partially-CFFT beam failed, in a ductile way, by a transverse rupture of fibers at the compression side indicating a confinement of concrete at the compression zone.
8) More experimental and analytical investigations are required to study the new rectangular partially-CFFT beam.

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