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Structural performance of new fully and partially concrete-filled rectangular FRP-tube beams

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HIGHLIGHTS

- Full-scale rectangular partially and fully-CFFT beams were tested under flexure.
- The strength-to-weight ratio of partially-CFFT beams reaches 370% higher than RC beams.
- The ductility of fully-CFFT beams is 12 times that of RC beams in average.
- The ductility of partially-CFFT beams is 5 times that of RC beams in average.
- The structural cracking, yield, and ultimate moments of CFFT beams can be predicted theoretically.

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ABSTRACT

This research introduces rectangular partially concrete-filled fiber-reinforced polymer (FRP) tube (CFFT) beams with inner voids and steel rebar. The beams contain an outer rectangular filament-wound FRP tube with an inner hollow circular or square FRP tube shifted toward the tension zone. The flexural behavior of the partially-CFFT beams was compared with a fully-CFFT beam, and another conventional steel-reinforced concrete (RC) beam having identical dimensions and flexural steel reinforcement. The results indicated that, the partially-CFFT beams had an overall strength-to-weight ratio 370% higher than that of the RC beam, while their weight was 30% lighter than the RC beam. In addition, the failure of the partially-CFFT beams was ductile in compression. The inner circular void indicated a slightly better performance than the square void in this partially-CFFT beam. Theoretical-section analysis has been conducted and compared with the experimental results.

1. Introduction

Fiber-reinforced polymer (FRP) composite materials have recently been used in the field of civil engineering constructions especially in corrosive environments. One of the innovative applications is the concrete-filled FRP tubes (CFFTs) which are becoming an alternative for different structural applications due to their high performance and durability. Extensive research was developed on CFFTs as columns, but comparatively limited research was carried out on CFFTs as beams ([12,10,16]; and others) and most of them concentrated on the circular section more than the rectangular one. However, the rectangular section has higher moment of inertia than the circular section. Hence, it has higher strength and flexural stiffness to resist the applied loads and deformations. Moreover, the construction and architectural requirements prefer the rectangular section of beams due to its stability during installation and its workability during connecting to other structural members like slabs and columns. To date, only two studies on the flexural behavior of rectangular CFFT beams have been reported [13,7].

CFFTs that are completely filled with concrete are not optimal for applications governed by pure bending, because the section is cracked and the concrete core contributes slightly to bending resistance and mainly prevents the tube from buckling. As such, the excess weight of concrete may increase transportation and installation cost. 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 the cracked concrete below the neutral axis [11,8,9,15,12]. While, limited trials were carried out on filament-wound FRP tubes especially those with rectangular section [13].

Fam and Rizkalla [12] investigated the effect of an inner hole by testing circular CFFT beams with an outer identical GFRP tube 168 mm diameter. One beam was totally filled with concrete, one

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beam had a central hole, and another two beams had similar holes, but they are maintained by concentric and eccentric inner GFRP hollow tubes 89 mm diameter. The results indicated that the strength of the CFFT beam with a central hole was 9% less than that of the fully-CFFT beam and providing an inner concentric GFRP hollow tube improved the strength by 7% more than that of the fully beam due to the additional reinforcement. Also, shifting the inner hollow tube toward the tension side was more effective, where the strength increased by 39% higher than the fully beam. Fam et al. [13] designed a rectangular section, 266 × 374 mm, of filament-wound FRP tube with an inner rectangular void. The strength of the voided section reached 78% of that completely filled with concrete. The hollow beam did not reach the target strength because it failed by inward buckling and fracture of the unsupported concrete flange at the compression side. Idris and Ozbakkaloglu [14] investigated the flexural behavior of FRP-high strength concrete (HSC)–steel composite beams by testing double-skin tubular beams (DSTBs) with outer FRP tubes and a central inner hollow steel section (HSS). The main parameters of study included the cross-sectional shapes of the inner HSS and the external FRP tube, concrete strength, presence or absence of concrete filling inside the steel tube, and effects of using mechanical connectors to enhance the bond between the steel tube and surrounding concrete. The results indicated that DSTBs exhibit excellent load–deflection behaviors with high inelastic deformations and minimal strength degradations (slightly increase of flexural strength after yielding). However, relatively large slippage can occur at the concrete–steel tube interface unless the bond is enhanced by mechanical connectors. Regardless the high flexural strength and stiffness of the DSTBs based on the inner steel tube, the weight and the bond remain critical issues in this design and need further investigations. The authors in this paper try to get benefit of each advantage of each design in the previous literature and to merge them together to develop a new partially-CFFT. A rectangular section is used to get benefit of the high sectional moment of inertia. A hole shifted toward the tension zone was provided by an inner FRP tube to increase the compression zone and to support the concrete at the compression side in addition to act as reinforcement. The beam is reinforced by steel rebar to increase the stiffness of the composite section. Finally, the design should achieve a full composite action.

2. Research significance

This research investigates the flexural behavior of full-scale rectangular CFFT beams, partially filled with concrete and reinforced with steel. The beams are consisted of identical rectangular GFRP tubes with inner hollow circular or square GFRP tubes shifted toward the tension zone. The space between the tubes is filled with concrete, which acts as a compression member and supports the tubes against buckling. The inner tubes act as a flexural reinforcement and support the inner concrete core at the compression zone. The beams are reinforced by additional steel bars at the tension side to enhance their stiffness and serviceability. The surfaces of tubes adjacent to concrete were roughened by sand coating to achieve the full composite action. The outer tubes provide permanent formworks, flexural and shear reinforcement, and protection against corrosion for the concrete and embedded steel. The partially-CFFT beams are compared to fully-CFFT beams and conventional RC beams, having identical dimensions and flexural steel reinforcement, to evaluate and compare their flexural behavior.

3. Experimental program

In this study, four groups of full-scale rectangular beams were tested under a four-point bending load and compared together. Each group contains two identical beams. The following sections provide a detailed description of the experimental work.

3.1. Fabrication of GFRP Tubes

Three different sizes of GFRP tubes were fabricated for this study (see Table 1): (1) A rectangular tube ($OR8_{30}$) had an internal cross section of 305 × 406 mm^2 and round corners with a 25 mm radius. (2) A circular tube ($IC4_{30}$) had an internal 218 mm diameter. (3) A square tube ($IS4_{30}$) had an internal cross section of 203 × 203 mm^2 and round corners with a 12.5 mm radius. The tubes were fabricated by filament-winding process and composed of a single end roving of E-glass fibers and vinyl ester resin. Based on the manufacturer data, the fibers have a nominal texture of 1100 gm/km, a maximum tensile strength of 2400 MPa, and modulus of elasticity of 80 GPa while the vinyl ester resin has a density of 1170 kg/m^3, a maximum tensile strength of 70 MPa, and modulus of elasticity of 3.5 GPa. The fibers are oriented at 90° and ±30° with respect to the longitudinal axis of the tubes. The orientation of fibers was chosen to increase the stiffness and strength of beam in the axial direction. After curing, standard tests were carried out to evaluate the physical and mechanical properties. Tension and compression tests were carried out according to ASTM D3039/D3039M [5] and ASTM D695 [6], respectively, on identical coupons to obtain the tensile and compressive strength in each direction. Thereafter, the tubes were cut to the required length of the beam prototypes. The inner surface of the outer tubes and the outer surface of the inner tubes (surfaces in contact with concrete) were sand coated by a layer of vinyl ester resin and coarse sand particles to produce a rough texture in order to enhance the bond between the concrete core and the tubes.

3.2. Beam specimens

A total of 8 beams with identical dimensions, 3200 mm long, were fabricated (see Table 2 and Fig. 1). Deformed steel bars No. 15M and No. 10M were used to reinforce the beams. According to the standard tension test ASTM A615/A615M [2], the yield tensile strength was 460 and 419 MPa for steel bars No. 15M and 10M, respectively, while their modulus of elasticity was around 200 GPa. Two identical conventional RC beams were reinforced with 4Φ15M as bottom steel reinforcement with a concrete cover equals to 38 mm, 2Φ10M as top steel reinforcement, and steel stirrups Φ10M@150 mm as shear reinforcement. Two identical CFFT beams ($OR8_{30}$) were completely filled with concrete and reinforced at the bottom with 4Φ15M. Two identical partially-CFFT beams ($OR8_{30}$–$IC4_{30}$) had identical outer tube and bottom steel reinforcement as $OR8_{30}$, but they had an inner circular void provided by a hollow circular GFRP tube ($IC4_{30}$) shifted toward the tension zone. Finally, two identical partially-CFFT beams ($OR8_{30}$–$IS4_{30}$) had the same configuration like $OR8_{30}$–$IC4_{30}$, but differed in the

Table 1
GFRP tubes configurations and mechanical properties.

Tube	Cross section (mm)	Stacking sequence	% Fibers (by weight)	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)
$OR8_{30}$	Rec. 305 × 406	[90°, ±30°, ±30°, 90°, ±30°, ±30°, 90°]	59	8.7	Ten. Test	16.4 ± 1.1	193 ± 18	18.4 ± 2	13.8 ± 0.9	164 ± 9	18.8 ± 1.3
					Comp. test	17.9 ± 1.4	−189 ± 9	−11.8 ± 0.5	13.7 ± 0.8	−199 ± 28	−16.7 ± 2.6
$IC4_{30}$	Cir. Ø = 218	[90°, ±30°, ±30°, 90°]	75	3.1	Ten. Test	16.7 ± 1.5	213 ± 16	16.7 ± 2.4	–	–	–
					Comp. test	20.4 ± 1.5	−130 ± 8	−7.0 ± 1	–	–	–
$IS4_{30}$	Square 203 × 203	[90°, ±30°, ±30°, 90°]	62	4.7	Ten. Test	16.4 ± 4.2	148 ± 8	14.2 ± 3.2	15.1 ± 1.4	120 ± 9	9.3 ± 1
					Comp. test	12.7 ± 1.1	−118 ± 5	−13.1 ± 1.7	10.8 ± 1.2	−127 ± 13	−13.5 ± 2.4