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Flexural behavior of rectangular FRP-tubes filled with reinforced concrete: Experimental and theoretical studies

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ABSTRACT

This paper presents experimental and theoretical investigations on the flexural behavior of rectangular concrete-filled fiber-reinforced polymer (FRP) tube (CFFT) beams with steel rebar. Seven full-scale CFFT beams, 3200 mm long and $305 \times 406\ mm^2$ cross section, were tested under a four-point bending load and were compared to two control steel-reinforced concrete (RC) beams. The CFFT beams had the same flexural steel reinforcement, but they had different wall thicknesses of filament-wound FRP tubes. The experimental results indicate an outstanding performance of the CFFT beams in terms of strength and energy absorption compared to the RC beams since their flexural strength and energy attained values 344% and 1052% higher than that of the RC beams, respectively. A strain compatibility/equilibrium model was developed to predict the moment-curvature response of the CFFT section addressing the issue of confinement and tension stiffening of concrete. The analytical results match well the experimental results in terms of moments, curvature, strains, and neutral axis location. Based on the model, the deflection can be predicted by integrating the curvatures along the span of the flexural member.

1. Introduction

In the last two decades, considerable research has been conducted to validate the application of fiber-reinforced polymer (FRP) composites in the construction industry. One of such innovative applications is the concrete-filled FRP tubes (CFFT). Extensive studies have been conducted to investigate the behavior of CFFTs as columns [1–19], but comparatively limited research was carried out on CFFTs as beams [20–28] and most of them concentrated on the circular section more than the rectangular one. However, 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, few studies on the flexural behavior of CFFT beams with rectangular section have been reported [25,28]. However, none of them reinforced the rectangular CFFTs with steel rebar or studied analytically their deflection response.

Most of the tested circular CFFT beams failed in compression [29]. This 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) were insignificant [29]. This notice is based on flexural tests of circular CFFTs without steel reinforcement. More investigations are required to verify that notice on rectangular CFFTs with steel rebar. Unlike steel-or-FRP-RC beams, the steel-reinforced CFFT beams can exhibit superior additional flexural capacities in the post-yielding stage [30,31]. This is attributed to the confining action of the FRP tube on the concrete core to withstand higher strains, and the FRP tube reinforcement contribution in the axial direction, in addition to the reinforcement action of the steel bars in their plastic hardening status. New design equations are required to get benefit of the outstanding flexural capacity at the post-yielding stage, and simultaneously, equations to predict the expected deflection with reasonable accuracy.

Analytical models have been developed to predict the flexural capacity and load-deflection response for circular CFFTs [23,24,32]. These models are based on strain compatibility, internal forces equilibrium, and material constitutive relationships. The forces within the CFFT cross section were calculated by integrating the stress over the area of each individual material. Despite the limited number of their tested specimens, these models predict well the flexural behavior of their circular CFFT beams. Their theoretical analysis depends mainly on a computer-based analysis and requires some sophisticated calculation procedures. Also, these proposed models require verification and adjustment to be valid

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for the rectangular CFFT beams, and need to be simplified to be applicable for common engineers.

This research focuses on the flexural behavior of rectangular CFFT beams with steel rebar, particularly in terms of flexural capacities at various stages during the loading, deflection response, and modes of failure, for which very limited published data exist. Also, it attempts to establish a theoretical basis for developing design procedure inspired by the North American design codes seeking for utilization of CFFT rectangular beams in field applications.

2. Experimental program

2.1. Beam specimens and materials

Four types of rectangular FRP tubes with identical internal cross sections were fabricated, at the laboratory of Composites Materials for Infrastructures at Sherbrooke University, using the filament-winding process. The FRP tubes were composed of typical E-glass fibers and vinyl-ester resin. The thickness of the tubes ranged widely from 3.4 to 9.9 mm in order to study its effect on the flexural behavior of the rectangular CFFT beams. Standard tests were carried out to evaluate the physical and mechanical properties of the filament-wound GFRP tubes. For example, tension and compression tests were carried out according to ASTM D3039 [33] and ASTM D695 [34], respectively, on identical five coupons to obtain the tensile and compressive strength in each direction. Table 1 lists the detailed physical and mechanical properties of the fabricated tubes. Note that the helical patterns were used to designate the fabricated tubes. For example, $OR4_{30}$ refers to an Outer Rectangular tube has 4 layers at 30°. The results of the coupons tests indicate slightly non-linear behaviors of the FRP composite, as shown in Fig. 1, which is attributed to the stacking sequence of the fibers. The inner surfaces of the tubes were 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 to achieve a full composite action under flexure.

Nine beams 3200 mm long were fabricated for this study as shown in Table 2; two identical steel-RC beams, two identical CFFT beams of $OR2_{30}$, $OR4_{30}$, and $OR8_{30}$, and one beam of $OR12_{30}$. All the tested beams were reinforced at the tension side with four steel bars 15 mm diameter (15 M) as flexural reinforcement with a concrete cover of 38 mm. Steel bars 10 M were used as shear and compression reinforcement in the RC beams only (see Table 2). According to the results of a standard tension test ASTM A615 [35] carried out on three specimens of a steel bar 15 M, the average yield tensile strength (f_y) is 467 MPa, the ultimate tensile strength (f_{su}) is 610 MPa, the modulus of elasticity E_s is about 200 GPa, the ultimate plastic strain equals 0.16, and the plastic hardening modulus is about 2 GPa ($\approx 0.01E_s$).

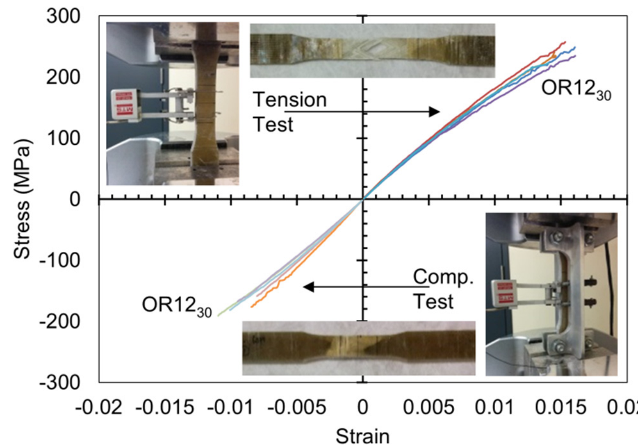


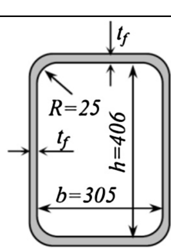
Fig. 1. Typical coupons test results in the axial direction.

The beams were casted with a ready-mixed normal weight concrete. The mix proportions for cubic meter of concrete includes 380 kg of cement, 152 L of water, 1070 kg of limestone aggregate with a maximum size of 14 mm, 718 kg of sand. 1 L of superplasticizer of polycarboxylate-based high range water reducing admixture, with a specific gravity of 1.7 and solid content of 32%, was added to the mixture before casting the tubes to enhance the concrete workability. The RC beams were casted in a horizontal wooden box formwork, while the tubes were fixed on inclined frames and the concrete was poured into the tubes from top end gates. The RC beams were cured in a conventional way by spraying water for 7 days. The CFFT beams were covered tightly with plastic sheets and the moisture surrounded the beams (under the cover) was kept at high level for 7 days. After 28 days of casting, concrete cylinders tests were performed according to ASTM C39 [36]. For every concrete batch, at least five standard concrete cylinders 150 mm diameter were tested under compression to get the compressive strength and three cylinders 150 mm diameter where tested under MTS machine with attached vertical strain extensometers to draw the stress-strain curve of the concrete. The average unconfined compressive strength for the cylindrical concrete specimens at 28 days old (f'_c) is listed in Table 2. Based on the stress-strain curves of the concrete cylinders, the experimental modulus of elasticity $E_{co} \approx 4500\sqrt{f'_c}$.

2.2. Test setup and instrumentations

The beams were tested using a four-point bending load setup over a simply supported span of 2920 mm and the distance between the applied concentrated loads was 720 mm centered

Table 1
GFRP tubes configurations and mechanical properties.

Tube	Cross section (mm)	Stacking sequence	% Fibers	t_f (mm)	Mechanical properties	Axial direction			Transverse direction		
						E_{lo} (GPa)	F_{lo} (MPa)	ε_{lo} (mm/m)	E_{tr} (GPa)	F_{tr} (MPa)	ε_{tr} (mm/m)
$OR2_{30}$		[90°, ±30°, 90°]	62	3.4	Ten. Test	14.3 ± 2.2	158 ± 20	15.7 ± 4.6	16.0 ± 1.3	257 ± 25.7	21.8 ± 2.1
					Comp. test	14.0 ± 2.9	−92.2 ± 9.0	−7.0 ± 0.7	17.8 ± 1.7	−175 ± 8.9	−10.4 ± 1.4
$OR4_{30}$		[90°, ±30°, 90°, ±30°, 90°]	61	5.7	Ten. Test	14.5 ± 1.2	173 ± 9.0	15.3 ± 1.9	14.4 ± 0.5	249 ± 24.9	23.9 ± 3.2
					Comp. test	15.5 ± 1.2	−165 ± 6.5	−12.5 ± 1.1	14.5 ± 0.7	−293 ± 17.9	−24 ± 3.5
$OR8_{30}$		[90°, ±30°$_2$, 90°, ±30°$_2$, 90°]	59	8.7	Ten. Test	16.2 ± 1.1	197 ± 15.7	18.9 ± 1.8	13.7 ± 0.9	168 ± 5.8	19.2 ± 1.2
					Comp. test	17.7 ± 1.2	−189 ± 9.2	−11.8 ± 0.5	13.8 ± 1.0	−211 ± 12.7	−17.8 ± 0.9
$OR12_{30}$		[90°, ±30°$_6$, 90°]	59	9.9	Ten. Test	18.6 ± 0.6	242 ± 12.8	15.3 ± 0.9	13.4 ± 0.9	125 ± 8.8	16.6 ± 2.1
					Comp. test	20.1 ± 1.7	−176 ± 12.4	−9.5 ± 1.2	12.2 ± 0.5	−217 ± 15.7	−24 ± 2.7