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Behavior of Concrete-Filled Near-Cross-Ply Filament-Wound GFRP Tubes Loaded in Combined Flexure and Torsion

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Abstract

The concrete-filled fiber-reinforced polymer (FRP) tube (CFFT) system lends itself well to structural applications such as columns, monopoles, and piers. In these applications, asymmetric loading can result in a combined loading state of flexure and torsion. Past research in the field of CFFTs has not examined the effects of combined loading with torsion. This paper presents the results of three circular CFFTs that were tested under different loading states to evaluate the effect of combined flexure and torsion. The samples were fabricated from ready-made near-cross-ply filament-wound glass FRP tubes filled with normal-strength concrete. These were tested under states of pure flexure, pure torsion, and equally combined flexure and torsion. The reductions in ultimate strengths of the CFFT in the state of combined loading were 19% for flexure and 25% for torsion. Also, there was a 30% reduction in the ultimate flexural deflection and a 64% reduction in the ultimate twisting capacity.

Keywords: CFFT, Combined, Flexure, GFRP, Torsion, Tube

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Introduction

Concrete-filled fiber-reinforced polymer (FRP) tubes (CFFT) are typically composed of an external filament-wound glass fiber-reinforced polymer (GFRP) tube filled with a concrete core. CFFTs are well suited to compressive elements such as columns due to their beneficial composite behavior that results from confinement of the concrete core [1]. Research has also studied the loading behavior of CFFTs under flexure [2], shear [3], and torsion [4] to name a few. The non-corrosive and stay-in-place features of the FRP tube lend themselves well to other applications including bridge piers and monopoles. Loading asymmetry is common in these structures where combined torsion and flexural loading can develop under typical loading conditions or under extreme events such as earthquakes. CFFTs under this potentially governing state of loading has not been studied.

Test Specimens

Three samples were fabricated and tested to evaluate the effect of combined flexure and torsion in circular CFFTs with near-cross-ply filament-wound GFRP tubes and normal-strength concrete. Table 1 shows the geometric and loading configuration for the three samples. The first two, (T) and (M), are control samples used to determine the ultimate pure torsion and pure flexural capacities, respectively. Sample (T+M) was tested under a state of combined loading with nearly equal amounts of torsion and flexure at failure.

Table 1: Test Matrix

Specimen	Shear Span, A (mm)	Extension Beam, B (mm, [-] to Mid-Span)	Torsion Beam, C (mm)	Loading Ratio (M/T)
(T)	250	-250	500	0 (Pure Torsion)
(M)	500	0	0	∞ (Pure Flexure)
(T+M)	500	0	500	0.94

The specimen configuration is shown in Figure 1. The overall length of each sample was 1800 mm. At either end of the CFFT, a 400 mm section was embedded into a concrete-filled square hollow structural steel sections creating an end-block for attaching the torsion loading apparatus. Within these embedded sections, prior to concrete filling, the tube was pinched to deform the circular section into a partial oval and a layer of epoxy and aggregate was provided on the outer surface. These measures ensured a proper bond between the tube and the concrete core as well as the tube and outer concrete of the end-block.

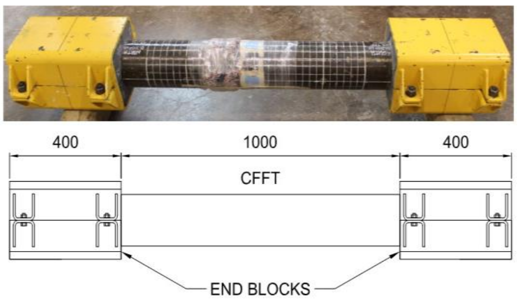

Figure 1: CFFT Specimen Configuration

Materials

Normal-strength concrete was used as the core infill for the CFFT. Standard concrete cylinders of 100 mm Ø x 200 mm were used in compression and splitting tensile tests. The average compressive strength and splitting tensile strength were 29.7 MPa and 3.4 MPa.
The FRP tube was a standard commercial product with an average diameter and wall thickness of 166 mm and 5.80 mm respectively. The tube wall consisted of 0.24 mm resin-rich outer layer, 2.84 mm structural layer, and 2.72 mm resin-rich chopped-fiber inner layer. The inner layer was a corrosion barrier for the tube that was designed to transport highly corrosive fluids. Table 2 lists the configuration of the structural layer. The fiber orientations were determined from burn-off tests and the layer thicknesses were determined from relative thickness ratios measured under microscope. The structural layers consisted of E-glass fibers and epoxy arranged in a near-cross-ply arrangement at $[86°/-9°]_3$ with the longitudinal axis of the tube.

Table 2: Structural Layer Configuration

Layer Number	1 (Outer)	2	3	4	5	6 (Inner)
Orientation [°]	86	-9	86	-9	86	-9
Thickness [mm]	0.72	0.41	0.60	0.34	0.51	0.26

The longitudinal tensile properties of the tube were determined from testing coupons cut from the tube. The coupons were 25 mm x 200 mm with the long dimension oriented with the longitudinal axis of the tube. Epoxy-bonded 50 mm GFRP tabs were used resulting in a 100 mm gauge length. The coupons were tested in a hydraulic universal testing frame with hydraulic grips at a rate of 1 mm/min. The longitudinal properties were based on the structural wall thickness of the tube. The average tensile strength of six coupons was 241.6 MPa and the average modulus of elasticity from three coupons was 26.0 GPa.

Testing Apparatus

A novel "Z" shaped testing apparatus capable of applying combined loading was developed as shown in Figure 2. This apparatus used a single hydraulic actuator running under stroke control at 2 mm/min to generate torsion and flexure. A spreader beam transferred the actuator load into two separate point loads on the sample. The applied loads were resisted by the reactions acting on the extensions of the torsion loading beams. The end view (Figure 2a) and bottom view (Figure 2d) demonstrate the equal but opposite arrangement of the torsion loading beams. The torsion loading beams were only used for the testing of (T) and (T+M) specimens, as no applied torsion was required for the (M) specimen. The side view (Figure 2b) shows that the configuration is comparable to a four-point bending test where the section between the applied loads is a constant bending moment region.
The dimensions shown in Table 1 and Figure 2 control the ratio of torsion and bending moment applied to the sample. The 'A' dimension represents the shear span and was measured from the center of the end-block to the location of the applied point load. This measurement controlled the constant flexural moment between the point loads. The 'B' dimension represents the position of the reaction force on the extensions of the torsion loading beams. This dimension controlled the fixed end moment applied to the sample. The dimension was measured relative to the center of the end-block and was taken as negative towards the CFFT mid-span, or positive towards the end of the sample. The 'C' dimension

was the perpendicular distance between the centerline of the CFFT and the reaction force. This determined the amount of constant torsion developed over the sample.
The testing configuration resulted in rotation of the torsion loading beams. This caused an outward displacement of the reaction forces that increased the moment arms that generated torsion shown as dimension ‘C’ in Figure 2. This movement was accommodated with supports consisting of a ball bearing within a track. The reported torsion value was corrected with the twist to account for this movement. The initial configuration of the sample (T+M) provided an equal ratio of torsion and flexure; however, the movement resulted in greater torsion relative to flexure at failure as reported in Table 1.

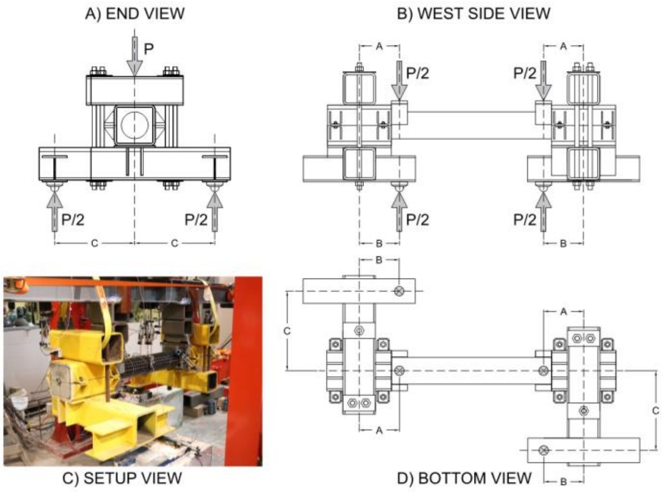

Figure 2: Testing Layout

Results and Discussion

The torsion-twist behavior of (T) and (T+M) are presented in Figure 3a. The addition of flexure was found to have very little influence on the torsional rigidity of the CFFT system. There were large differences in the ultimate capacity, where the addition of the flexure resulted in a 25% reduction in the torsional capacity. A more significant effect was seen in the 64% reduction in the ultimate twist capacity. This is attributed to (T+M) failing prior to the plateau seen in (T). This plateau accounts for a significant amount of the twist sustained by the pure torsion sample (T). The plateau was caused by the non-linear matrix-dominated behavior occurring as a result of the off-axis loading of the fibers in each lamina and the progressive failure of the laminate.
Figure 3b demonstrates the bending moment-deflection behavior of samples (M) and (T+M). Like the torsional behavior in the previous section, the presence of torsion had little effect on the flexural rigidity. The ultimate bending moment and the ultimate deflection were both found to decrease in the presence of moderate levels of torsion. Sample (T+M) experienced a 19% reduction in flexural capacity and a 30% reduction in ultimate deflection.
In all cases, failure occurred from rupture of the FRP tube where damage extended vertically from the bottom of the specimens. (T) and (T+M) ruptured through the entire depth, whereas (M) ruptured only partly through the flexural compression region. All samples had a concrete crack mirror the tube rupture. Removing the tube showed (T) had a distributed network of spiral concrete cracks aligned at approximately 45°. (T+M) had spiral cracks at approximately 60° with few cracks extending into the flexural compression region. (M) had a

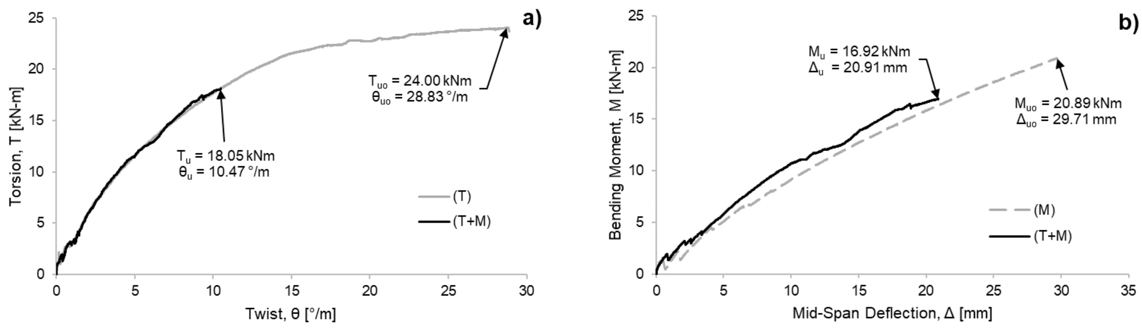

Figure 3: Test Results, a) Torque-Twist and b) Bending Moment-Deflection

flexural crack extending up to the neutral axis near mid-span. Additionally, (T+M) and (M) had two flexural cracks, near each point load, that extended through the entire section depth. The data showed no discrete bond slip event and visual inspection at the exposed ends of the samples showed no slip between the core and the tube.

When the tube ruptured, concrete restraint was lost, and complete failure of the system occurred immediately. In pure torsion, the FRP tube is in a combined state of tensile hoop, tensile longitudinal, and shear stresses. Under pure bending moment, in a shear-free region, the FRP tube is loaded primarily in tension and compression in the longitudinal direction and minor hoop stresses resulting from Poisson's ratio [2]. In a state of combined torsion and bending moment, the stresses in the tube accumulate rapidly, particularly longitudinal tensile stresses on the bottom face of the tube. This state of combined loading is the most likely source of the change in ultimate capacities.

Conclusion

Three circular CFFTs with near cross-ply fiber arrangements were tested in order to evaluate the effects of combined torsional and flexural loading. The results demonstrated that torsional and flexural rigidities did not change significantly under combined loading. When compared to states of pure torsion and pure bending moment, the sample under combined loading experienced a 25% reduction in torsional strength and a 19% reduction in flexural strength. More importantly, the combined loading sample experienced a 64% reduction in twisting capacity and a 30% reduction in deflection capacity. The change in ultimate strength is primarily associated with the change in the state of stress in the FRP tube.

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