



Laval (Greater Montreal)

June 12 - 15, 2019

*FLEXURAL BEHAVIOR OF RECTANGULAR CONCRETE FILLED FRP TUBES (CFFT) BEAMS POST TENSIONNED WITH STEEL TENDONS*

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**Abstract:** The growth in the demand for prestressed concrete (PC) in the construction industry has steadily increased with time due to the superior performance and economy offered by PC over conventional reinforced concrete (RC) in a large number of structural engineering applications. Introducing prestressing for the concept of concrete-filled fiber-reinforced polymer (FRP) tube (CFFT) can provide this system many unique advantages, which makes it a good alternative for innovative sustainable and high-performance structures. This paper reports the test results of an experimental investigation aimed at evaluating the effect of longitudinal prestressing on the flexural performance of rectangular CFFT beams. Three full-scale beams were constructed and tested under a four-point bending over a span of 3.00 m. Of the three, two were reinforced CFFT beams with and without prestressing strands and one conventional prestressed (PRC) beam for comparison. All beams had identical cross-sectional of 305×406 mm<sup>2</sup>. The test results confirm the feasibility of prestressing for rectangular CFFT as flexural members. Prestressed rectangular CFFT beam show excellent load-deflection behaviour with high inelastic deformation and ultimate capacity compared to their counterparts CFFT with no prestressing and PRC beams. Prestressing could enhance the confinement effect of the concrete core under bending, which, in turn, improves the prestressed CFFT beam performance in deflection, strength, stiffness and ductility. The promising results can provide impetus for constructing prestressed rectangular CFFT under bending and constitute a step forward towards sustainable and high-performance hybrid structural elements.

## 1 INTRODUCTION

Constructed infrastructure is aging with time and deteriorated due to a number of attributes such as corrosion, moisture, and chemical incompatibility. Thereby, the longevity of structural members is reduced. Corrosion damage is recognized as a crucial factor affecting the performance of concrete structures and corresponding consequences are significant. Although concrete cover retards the ingress of harmful matters into the structure, the occurrence of corrosion is inevitable in most reinforced or prestressed concrete members. The use of fiber-reinforced polymer (FRP) composites as a confining material for concrete has received significant research attention. Concrete-filled FRP tubes (CFFT) became a popular form of hybrid structural elements in rehabilitation or in new construction. Filling the FRP tube with concrete can provide compressive resistance and prevent local buckling of the thin tube (Roeder et al. 2010). The CFFT system can be also internally reinforced with steel reinforcement, as the tube can protect the steel from water infiltration and corrosion, while the steel reinforcement can provide ductility and additional strength as well as minimize slip of the tube relative to the concrete core, which can be a major factor in the loss of composite action (Abouzied 2016; Abouzied and Masmoudi 2016, 2017, Ahmed A. et al. 2018b). Therefore, utilization of FRP tubes filled with plain or reinforced concrete as a hybrid composite system can provide the proposed system many unique advantages, which makes it highly suitable alternative for use in the construction of sustainable and high-performance structures (Fam et al. 2005; Ahmed A. et al. 2018 a; Ahmed A. and Masmoudi, 2018;

Ahmed A. et al. 2018c). The feasibility of CFFT system has been expanded for flexural members such as bridge beam applications. In addition, it can be prestressed to further improve its effectiveness, particularly for serviceability issues such as deflection and crack control. Introducing the prestressing to CFFT may activate the confinement mechanism induced by the FRP tube and would lead to considerable enhancement of strength and stiffness (Mirmiran and Shahaway 1999; Fam and Mandel 2006 a&b). Therefore, prestressed CFFT results in an increase in the economical range of application of reinforced concrete (RC) or non-prestressed CFFT. Despite its demonstrated benefits in terms of improving structural behavior, there still is a lack of research, including the functional reliability of CFFT flexural members, particularly rectangular cross-section.

The work presented in this paper is a part of an extensive research project was undertaken at the University of Sherbrooke (Quebec, Canada) to elucidate the flexural behaviour of post-tensioned rectangular CFFT beams. Full-sized post-tensioned rectangular CFFT beams were constructed and tested under a four-point bending. The purpose was to assess the effectiveness of prestressing on the flexural performance of rectangular CFFT beams and to compare its behaviour with non-prestressed CFFT and conventional prestressed RC beams. The pioneer test results of this research will contribute to better understanding the flexural behaviour of prestressed CFFT beams. The research also will contribute to the development of design recommendations for prestressed rectangular CFFT under bending.

## 2 EXPERIMENTAL PROGRAM

### 2.1 Material Properties

Three materials were used in fabricating the test specimens. These materials were GFRP tube, concrete, and steel strands and bars. The following sections provide a description of different materials were used herein.

#### 2.1.1 GFRP Tubes

Rectangular glass FRP tubes - namely Types I & II - with identical internal cross-sectional dimensions of 305 mm x 406 mm were fabricated, at the laboratory of Composites Materials for Infrastructures at University of Sherbrooke, using the filament-winding process. The FRP tubes were composed of typical E-glass fibers and vinyl-ester resin. The tubes had the same fibers stacking sequence (90°, ±30°, 90°, ±30°, 90°) with thicknesses of 5.6 and 5.7 mm for tubes I and II, respectively. Tension and compression standard tests were carried out according to ASTM D3039 (2010) and ASTM D695 (2008) on five representative coupon samples to determine the tensile and compressive mechanical properties in longitudinal and hoop directions, respectively. All tubes were sand-coated on the inner surface along the entire length of the tube to improve bonding between the tube and surrounding concrete. Table 1 reports the mechanical properties of the fabricated tubes. Figure 1 shows the standard tests for the tested samples in tension and compression.

Table 1: GFRP tubes mechanical properties

Properties	Type I	Type II†
Wall thickness (mm)	5.6	5.7
Axial tensile strength (MPa)	170	173
Axial compression strength (MPa)	162	165
Hoop tensile strength (MPa)	252	249
Hoop compression strength (MPa)	295	293
Elastic modulus-Axial (GPa)	15.3	15.0
Elastic modulus-Hoop (GPa)	14.7	14.5

\* Angles measured relative to the longitudinal direction of the tube

† Tested by Abouzied and Masmoudi (2015)



a) Compression                      b) Tension

Figure 1: Standard coupons tests and samples

### 2.1.2 Concrete

The specimens were cast using a ready mixed normal-strength concrete (NSC) with target compressive strength of 40 MPa after 28 days. A maximum aggregate size of 14 mm was used. A superplasticizer was added during casting to enhance the concrete workability. The development of concrete strength with age were monitored in accordance with ASTM C39/C39M9 by tests of 100 x 200 mm concrete cylinders that were cured adjacent to the beam specimens under similar conditions. There were at least three cylinders in each casting which was tested at 7, 14, and 28 days after casting and throughout the beam testing period. The actual concrete compressive and tensile strengths at the day of testing were determined based on the average values of six cylinders (100 × 200 mm) of each test. The average concrete compressive and tensile strengths were 43 MPa and 3.8 MPa, respectively.

### 2.1.3 Steel Strand

Steel strands of 0.6-in.-diameter (15 mm), seven-wire, low-relaxation strands with a cross-sectional area of 140 mm<sup>2</sup> were used. The strands had a Young’s modulus of 197 GPa and ultimate strength of 1950 MPa. The strand yield strength, corresponding to a 1% elongation, was 1802 MPa, and the rupture strain was 7%. The mechanical properties of the steel strands obtained from testing are presented in Table 2.

### 2.1.4 Deformed Steel Bars

Two different deformed steel bars were used to reinforce the control and PCFFT specimens. Deformed steel bar 15M (16-mm in diameter; 200 mm<sup>2</sup> in cross-sectional area); were served as bonded reinforcement at the tension side of the test specimens as specified in the CSA A23.3 (2014) for unbonded tendons and maximum permit tensile stresses less than 0.5√f<sub>c</sub>. On the other hand, deformed steel bars 10M (11.3 mm in diameter; 100 mm<sup>2</sup> in cross-sectional area) were used as steel stirrups for the control specimens. The mechanical properties of the steel bars were determined from testing five representative samples for each diameter according to ASTM A615/A615M-09 (2009). The mechanical properties of the steel bars are presented in Table 2.

Table 2: Mechanical properties of steel strands and reinforcing bars

Reinforcement type	Nominal diameter (mm)	Nominal area (mm <sup>2</sup> )	E <sub>r</sub> (GPa)	Yield strength (MPa)	Ultimate strength (MPa)	Yield strain (%)	Prestress force*	
							Jacking (kN)	Effective (kN)
0.6-in (strand)	15.2	140	197	1802	1950	0.091	208.6	170
10M (deformed)	11.3	100	200	420	610	0.021	-	-
15M (deformed)	16.0	200	200	460	620	0.024	-	-

\* Based on 0.65 f<sub>pu</sub>

## 2.2 Test Specimens

All beams were tested as a simply supported in a four-point bending setup under monotonic loading. The span, measured between the centres of the supports, was 3.0 m and the length of the constant moment region between the two-point loads was 0.7 m with a span to depth ratio of 8.7. The prestressed CFFT beam was reinforced at the tension side with deformed steel bars 2-15M as minimum bonded reinforcement with a concrete cover of 38 mm while at the beams ends, it was reinforced with steel stirrups 10M@100 mm for a distance of 500 mm to avoid any anchorage failure at the end anchorage zones. Internal ducts were provided using polyethylene tubes (nominal pipe size 1 inch). This diameter was intended to accommodate the strain gauges attached to the strands and wires. The strands had an eccentricity ( $e$ ) of 85 mm. The eccentricity was measured from the inner surface of the FRP tubes to the center of the ducts. All beams were tensioned with the same prestressing level of 0.65 fu. Prestressed CFFT beams were cast in an inclined position on a steel formwork specially fabricated for this investigation whereas the tubes serve as a stay-in-place formwork for concrete while prestressed control beam was cast in a horizontal position in a wooden formwork. Table 3 presents the specimens' detail in this investigation.

## 2.3 Instrumentation, Test Setup, and Loading Program

Extensive instrumentation was used to help understand specimens' behavior. Two electrical strain gauges were mounted before casting on the bottom flexural-reinforcement bars at the beam mid-span. Before testing, all specimens were instrumented at midspan. Axial and transverse strains gauges, 6 mm long, were bonded on the outer tubes surface at the top and bottom faces, corners, and at different levels of the beam depth as shown in Figure 2. Besides, strain rosettes were located at the center of the shear span and the mid-height to investigate the shear response of the beam. The specimens were instrumented with potentiometers transducers (PTs) at mid-span, the point of application of concentrated loads, and at the mid-distance between loading points and supports to record the vertical displacements along the beam. Furthermore, two PTs were used at the both ends to monitor any slippage between the concrete and the GFRP tube. Two linear variable differential transducers (LVDTs) were also used on the extreme top and bottom surfaces of the tube to measure the longitudinal strains.

The beams were tested using a four-point bending over a span of 3.00 m and the load was transferred through a steel loading beam at two locations spaced 0.7 m apart as shown in Figure 3. The load was applied monotonically in a displacement control using a 10,000 kN MTS machine at a rate of 1 mm/min. The steel strands were anchored at both end using wedge and barrel supported on end bearing steel plates. The prestressing force were applied by tensioning the steel strands at one end (live end) at the same time using hydraulic jacks. The prestressing forces were carefully applied in five increments up to the desired prestressing force. Prestressing forces in each cable were monitored and verified by three different means: load cells at the dead end, steel strands strain gauge readings, and jacks oil pressure gage. An insignificant difference in the prestressing forces were measured in each prestressing strand.

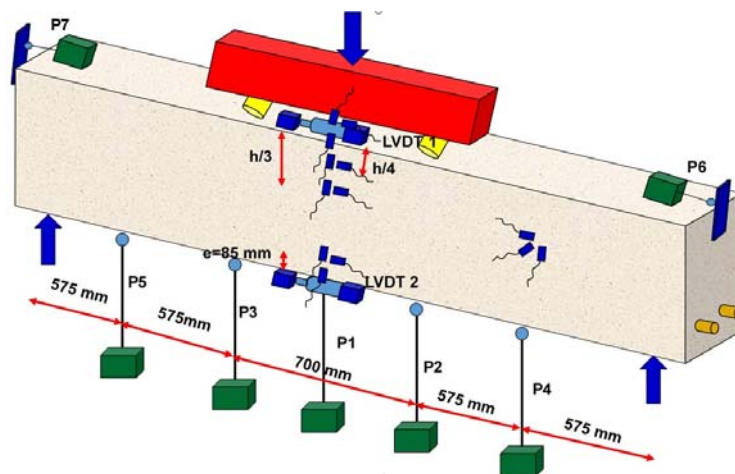


Figure 2: Details of instrumentations

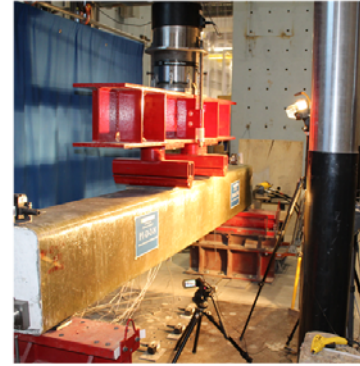
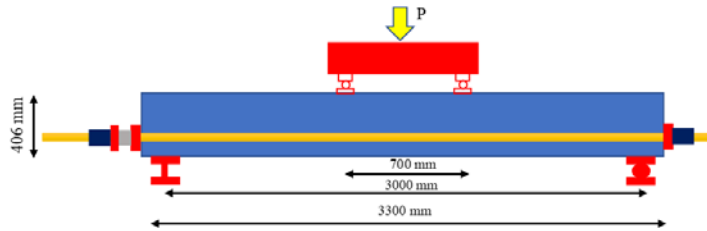


Figure 3: Test setup and Schematic

### 3 TEST RESULT AND DISCUSSION

#### 3.1 Mode of Failure

Figure 4 shows the mode of failure for the tested specimens. Prestressed CFFT beam (B2) failed under flexural mode of failure in the tension side with no signs of shear failure or web buckling. The GFRP compression flange of B1 showed minor signs of outward local buckling. However, the tested specimen continued to carry additional loads until it eventually failed in the tension side. No slippage was observed between the concrete core and GFRP tube during testing of the specimens. This suggests that sufficient bond strength was developed and may have been further enhanced by the radial pressure exerted by the tube through confinement of the prestressed concrete (Fam and Mandal 2006). It is worth mentioning that similar mode of failure was observed when compared to their counterpart CFFT beam with no prestressing tested by Abouzied and Masmoudi (2017). This indicates that the mode of failure of the tested specimen was dependent on the tube rather than the prestressing reinforcement. On the other hand, prestressed reinforced concrete beam (PRC-B1) failed by crushing and spalling of the concrete cover after yielding of the tension steel bars and strands.

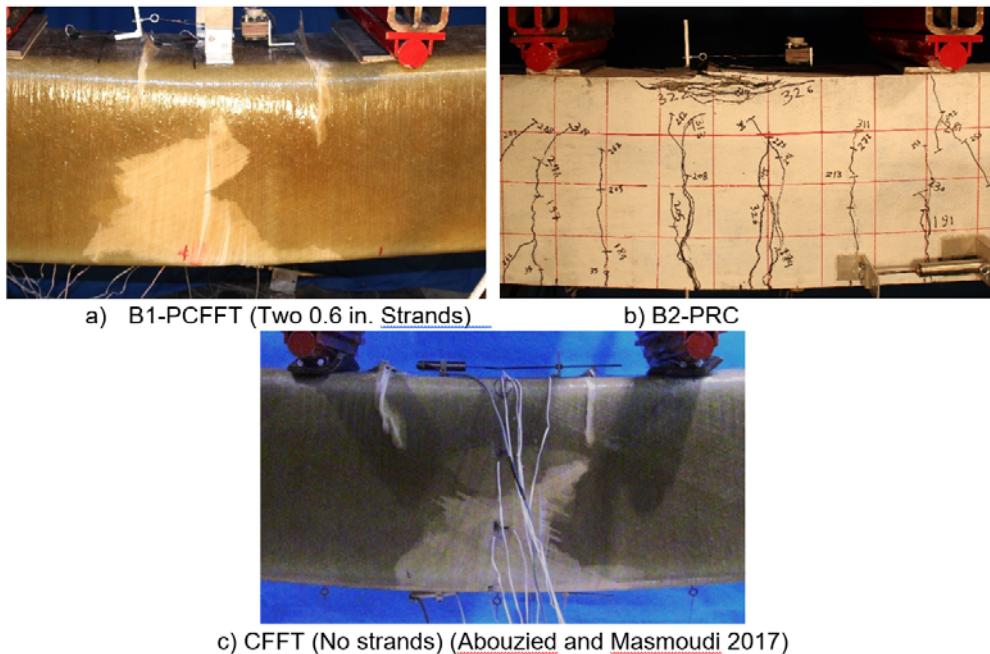


Figure 4: Mode of failure of the tested specimens



Table 3: Test specimen's details and test results

ID	Tube types	$f_c$ (MPa)	No. of strands	$A_{s_{rt}}$	$P_u$ (kN)	$\Delta u$ (mm)	Failure Mode
B1	---	43	2	2 M 15 (T&B)	331	38.2	Tension
B2	i	43	2	2 M 15 (B)	840	109.7	Tension

### 3.2 Load-Deflection Responses

Figure 5 shows the load-deflection responses of the tested specimens. Generally, all prestressed specimens exhibited linear behavior and similar stiffness until cracking. Thereafter, nonlinear behavior increased after steel yielding and continued until failure. Specimen B1-PRC exhibited a near plastic response after yielding whereas CFFT beams with and without prestressing showed an ascending nonlinear trend due to the presence of the GFRP tubes until it reached the maximum load. As seen in Figure 5 the maximum load of B2-PCFFT was higher than that of B1-PRC and non-prestressed CFFT beams tested by Abouzied and Masmoudi (2017). For any given load beyond cracking, the deflection of B2-PCFFT was smaller than that of B1-PRC. The FRP tube provided a reinforcing effect in the longitudinal direction, which is not provided by the steel stirrups as well as has a confining effect on the concrete core that is more effective than the steel stirrups because the tube is located at the outermost surface and thus confines a larger concrete area. Thus, the GFRP tube improved significantly the ultimate strength and stiffness and also the energy absorption capacity. This coincided with the experimental results for circular prestressed CFFT beams by Fam and Mandel (2006). On the other hand, the CFFT Specimen evidenced lower initial stiffness than specimen PCFFT (see Figure 5). The non-prestressed CFFT tested by Abouzied and Masmoudi (2017) showed an almost trilinear behavior. The first slope represents the member before concrete cracking, a second slope represents a reduced stiffness once steel bars yielded, and a third slope depicts the non-linear post-yielding behavior, whereas the prestressed CFFT specimen has almost similar response but another transition slope was depicted after the yielding of the steel strands. In general, prestressed CFFTs beams achieved a significant improvement compared to their counterpart CFFT without prestressing. Prestressing activates the confinement mechanism of the concrete core restrained by the FRP tube and would lead to considerable increases in their cracking strengths, initial stiffnesses, and ultimate moment capacities. The ultimate failure load was increased by 23.2% for B2 compared to their companion without prestressing CFFT beam tested by Abouzied and Masmoudi (2017).

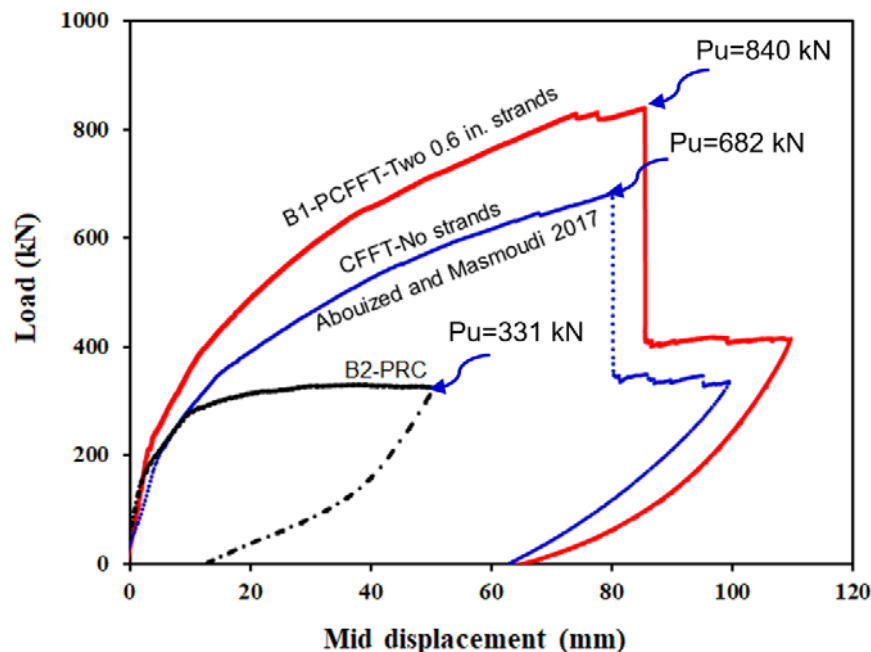


Figure 5: Load deflection responses

## 4 CONCLUSIONS

On the basis of the experimental test results presented in this paper, the following conclusions can be drawn:

1. The prestressed rectangular CFFT beams evidenced a substantial higher ductility, stiffness, and superior strength compared to the prestressed RC beams. The non-corrosive tubes would most likely protect steel strands from corrosion induced by external environments.
2. Prestressed rectangular CFFT beam showed excellent load-deflection behaviours with high inelastic deformations and ultimate capacity compared to their counterpart CFFT with no prestressing.
3. Prestressing could significantly enhance the confinement effect of the concrete core under bending, which, in turn, improves the prestressed CFFT beam performance in deflection, strength, stiffness and ductility.
4. This study confirmed the feasibility of using post-tensioned rectangular CFFT system for flexural members such as girders in bridge and marine applications, which will have a significant impetus for the development of new structural members. Prestressed rectangular CFFT beams could be a major enabling technology towards sustainable and high-performance structures.

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