university of Waterloo

Department of Civil Engineering
Faculty of Engineering

University of Waterloo
200 University Avenue West
Waterloo, Ontario, Canada
N2L 3G1

519-888-4567
Fax 519-888-6197

TENSILE CAPACITY OF DRAPED CFRP TENDONS

REPORT

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Prepared for:

Gene Latour

President
Trancels-Pultrall Canada Inc.
109 Bayfield Street Suite 203
Barrrie, ON L4M 3A9
Ph. (416) 410-2564 or (705) 734-2340

Prepared by:

Principal Investigator: Professor Khaled Soudki, PEng
Research Assistant: Martin Noël, EIT

Department of Civil and Environmental Engineering
University of Waterloo, Waterloo Ontario N2L 3G1
Tel. (519) 888-4494/ soudki@uwaterloo.ca

1. Introduction

1.1 General

Fibre-reinforced polymer (FRP) materials are gaining widespread acceptance throughout the construction industry for use in reinforced and prestressed concrete structural applications as an alternative to conventional steel reinforcement and prestressing strands. Carbon fibre-reinforced polymers (CFRPs) are especially attractive for prestressed concrete because of their high strength-to-weight ratio, low relaxation and corrosion resistant properties. In addition, CFRPs have a lower axial stiffness compared to steel which results in reduced prestressing losses due to creep and shrinkage of the concrete as well as elastic shortening of the concrete member (ACI 2004, ISIS Canada 2008).

In prestressing applications it is often desirable to vary the tendon profile in order to counter the effects of applied loads efficiently. This effect is often achieved through the use of harping points which apply a lateral load to the prestressing tendon to produce the desired profile. In the case of FRP tendons, this lateral stress can significantly reduce the overall tensile capacity causing premature rupture of the fibres. Increasing the radius of the deviator at the harping point results in a more gradual distribution of lateral load and reduces the risk of premature failure. The effect of the size of deviator radius on the tensile capacity of CFRP tendons is investigated in this study.

1.2 Objectives and Scope

The objective of this research study is to evaluate the tensile capacity of CFRP tendons under different harping configurations achieved by changing the radius of deviator plate used. Two deviator plates were used having radii of 250 and 500 mm, respectively. A total of five CFRP bars were tested for each size of deviator plate. The harping angle was kept constant at 2.2%.

2. Test Setup

2.1 Material Properties

The CFRP bars used were Carbon V-Rod bars manufactured by Pultrall Inc. Each bar had a diameter of 12.7 mm and a cross-sectional area of 126.7 mm^2. The length of the bar was 20 feet (6.1 m). These bars are generally produced with a sand coating to facilitate enhanced bond with concrete; however, specifically for use in this study 750 mm was left uncoated at each end and at the center of the bar to allow for anchors to be seated at each end and to reduce friction against the deviator plate at the center.

Material properties for the CFRP bars are provided by the manufacturer (Pultrall 2007). The tensile strength of the straight bar is 1899 MPa with a guaranteed design tensile strength of 1765 MPa. The modulus of elasticity is 144 GPa and the bars have an ultimate elongation of 1.32%.

2.2 Test Frame

The test frame used was adapted from a previous study which allowed for a variety of harping angles and deviator plates to be used. The general configuration is shown in Figure 1 (Quayle, 2005). The test frame was bolted to the structural floor using steel base plates (Figure 2a). Wedge type anchors developed at the University of Waterloo were used to anchor the CFRP rods at each end as shown in Figure 3. Anchor pivots at each end of the test frame allowed free rotation of the anchor in the vertical plane while restraining the tendon anchors in their longitudinal direction. At the jacking end, the plate in the anchor pivot was threaded to accept the hydraulic cylinder used to apply the tensile load to the test specimens. An electric hydraulic pump with a variable flow valve was used to control the rate of loading.

The anchor pivots were spaced 18 feet from center to center, with the deviator forks located directly between the two. The deviator forks at the center of the test frame had a series of bolt patterns which allowed for simple interchanging of deviator plates. The bolt patterns were pre-existing from a previous study and permitted a harping angle of 2.2% instead of exactly 2% as desired. The deviator plates used are shown in Figure 4. These plates were cut from 25 mm (1 inch) thick steel plate, with a polished curved bearing surface to minimize friction with the tendon. These plates were mounted into the deviator forks using two bolts.

2.3 Safety Precautions

Due to the violent nature of failures caused by tendon rupture, several steps were carried out to ensure that the failure was properly contained and to reduce risk of injury or equipment damage. A box was built around the test setup using plywood panels on the sides and heavy impact-resistant Kevlar explosion blankets as a removable cover as shown in Figure 2b. In addition, a restraining mechanism, shown in Figure 5, was designed to restrain the end anchorages at failure and prevent damage to the load cells. As an extra precaution, sand bags were placed at each end as a final barrier to bar fragments.

2.4 Instrumentation and Data Acquisition

Barrel type load cells were used at both the dead and jacking ends between the anchor and the pivot. These load cells recorded the applied load and were also useful to determine the friction loss in the tendon over the deviator plate. Two tendons for each size of deviator plate were also instrumented with 5 mm electrical resistance strain gauges placed longitudinally on the bar, one gauge directly over the deviator plate where the maximum strain was expected to occur and a second gauge on the straight portion of the bar between the deviator and the jacking end. All data was recorded using a computer controlled data acquisition system (DAQ).

2.5 Test Procedure

After the appropriate deviator was bolted into place in the deviator forks, the CFRP bar was placed into the frame with each end inserted through the anchor pivots. The anchors were pre-seated prior to applying any load in order to prevent anchor slip. The safety blankets were then tied down over top of the test frame and slack in the tendon was removed by loading the hydraulic jack until there was no gap between the anchors and anchor plates. At this point the sand bags were placed at each end and tension loading of the tendons commenced. After failure of each specimen, the fragments were removed prior to installation of the following bar.

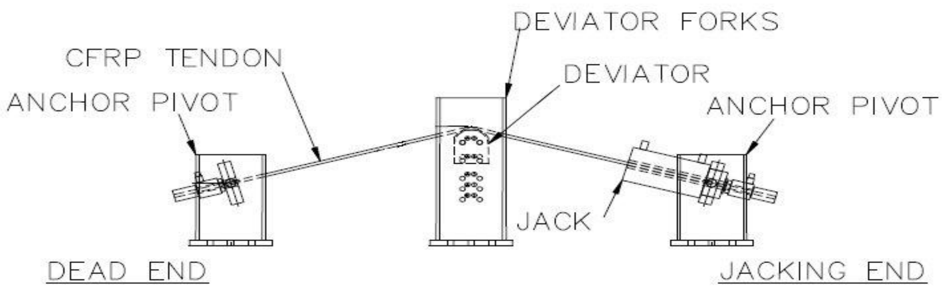

Figure 1 - Schematic of test frame

Figure 2 - a) Test setup, and b) Protective box and removable blanket

Figure 3 - CFRP anchor

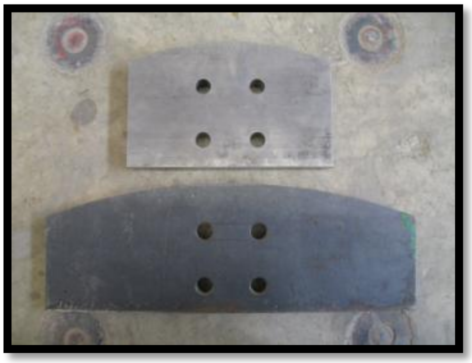

Figure 4 - Deviator plates

Figure 5 - End restraint

3. Test Results

3.1 250 mm Deviator Radius

Results from tension tests using a deviator with a 250 mm radius at a harping angle of 2.2% are summarized in Table 1.

Table 1 - Results from 250 mm deviator radius

Test Number	Maximum Jacking Load (kN)	Maximum Dead End Load (kN)	Maximum Stress (MPa)	Maximum Strain in Straight Bar (x 10^{-6})	Maximum Strain over Deviator Plate (x 10^{-6})
1	108.1*	105.6	853.4	7155	8518
2	124.0*	121.0	977.9	7124	10061
3	123.0	120.6	971.0	--	--
4	121.5	117.7	958.6	--	--
5	126.9	122.6	1001.3	--	--
Average	120.7	117.5	952.4	--	--

*Values calculated using average load ratio of jacking end to dead load

The results above clearly demonstrate that using deviators with small radii for harped prestessing tendons introduces sharp lateral forces which significantly reduce the tensile capacities of the bars. The average tensile strength of the CFRP tendons draped over a 250 mm radius deviator plate was only 54% of the guaranteed tensile capacity of the straight bar.

Strains over the deviator plate were also significantly higher than in the straight portion of the bar due to bending. Typical stress-strain plot of a CFRP bar tested using a 250 mm radius deviator at a 2.2% harping angle is shown in Figure 6.

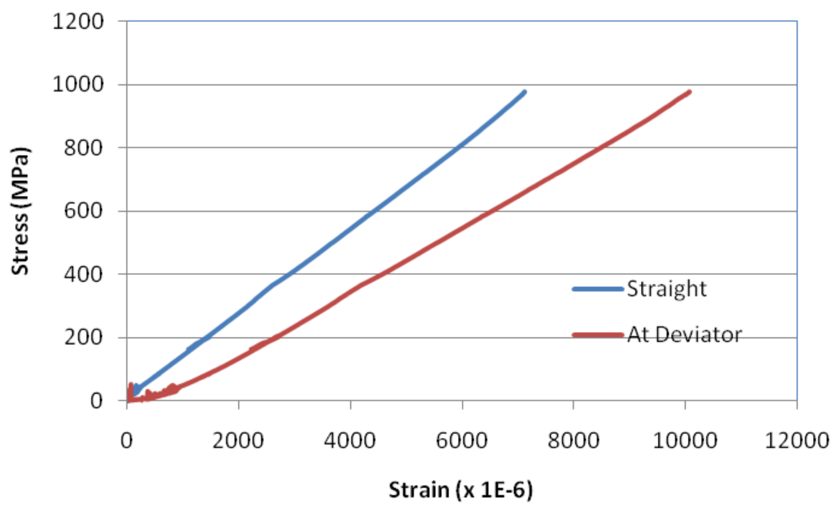

Figure 6 - Stress-strain relationship for DT250-2

3.2 500 mm Deviator Radius

Results from tension tests using a deviator with a 500 mm radius at a harping angle of 2.2% are summarized in Table 2.

Table 2 - Results for 500 mm deviator radius

Test Number	Maximum Jacking Load (kN)	Maximum Dead End Load (kN)	Maximum Stress (MPa)	Maximum Strain in Straight Bar (x 10^{-6})	Maximum Strain over Deviator Plate (x 10^{-6})
1	131.6	120.9	1039.0	7050.2	9577
2	129.2	121.0	1019.8	7687	9850
3	142.6	133.3	1125.7	--	--
4	122.3	114.0	965.5	--	--
5	123.7	119.1	976.3	--	--
Average	129.9	121.7	1025.3	--	--

It is evident that increasing the radius of the deviator plate to 500 mm slightly increased the tensile capacity of the draped CFRP tendons. The average ultimate strength was approximately 58% of the guaranteed strength of a similar straight bar.

As with the previous specimens, the strains over the deviator plate were higher than in the straight portion of the CFRP bar as shown in Figure 7.

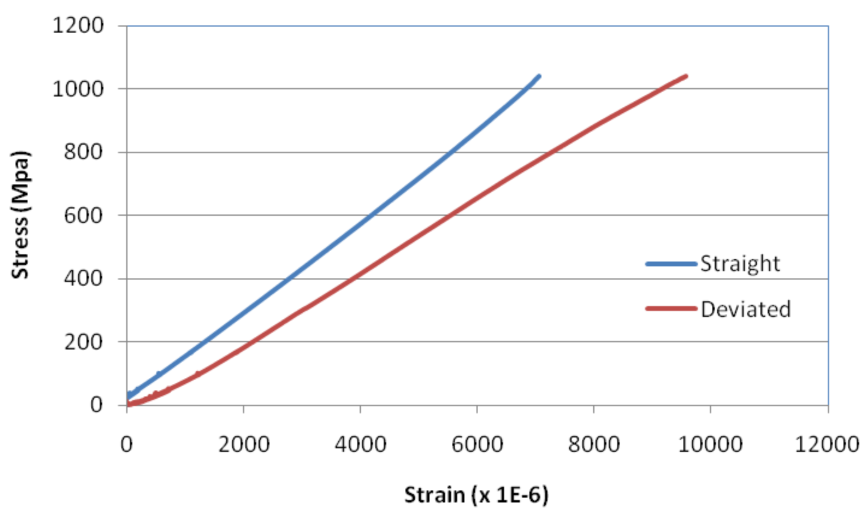

Figure 7 - Stress-strain relationship for DT500-1

3.3 Failure Mode

The CFRP tendon ruptures were violent and brittle. CFRP materials are linearly elastic to failure, and as such do not yield. Failures initiated by rupture of individual fibres which delaminated and bar fragments were scattered in all directions. Due to the high loads at which failure occurred, high levels of energy were dissipated at failure resulting in high velocity fibre fragments, which were successfully contained by the protective measures implemented. Examples of failed specimens are shown in Figure 8. As can be clearly seen in Figure 9, failure did not initiate at the anchors demonstrating that the anchors used were successful in transferring the load to the bar without damaging the fibres.

Figure 8 - Tendon rupture failures

Figure 9 - Tendon anchors after failure

4. Conclusions

Several conclusions can be drawn from the test results:

1. Lateral loads resulting from the use of harping points can significantly reduce the tensile capacity of CFRP prestressing tendons.

2. Increasing the radius of the deviator plates used to create a harping point can increase the tensile capacity of the draped CFRP tendon although the full capacity of the straight bar is not reached.

3. Strains in the CFRP tendon over the deviator plate are significantly higher than in the straight bar portion as a result of bending in the bar.

4. Carbon V-Rod bars can be successfully used in prestressing applications with harping points provided a sufficient radius is used for the deviator (a minimum of 500 mm is recommended) and the jacking stress does not exceed 45% of the guaranteed design tensile strength of the straight tendon.

5. Acknowledgement

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6. References

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