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Development and Assessment of a Mechanical Strengthening System for Post-tensioned Concrete Bridge Cantilever Wings Using Post-tensioned CFRP Rods

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Abstract:

This paper presents the development and experimental assessment of a mechanical strengthening system using post-tensioned (PT) carbon fibre reinforced polymer (CFRP) rods for the rehabilitation of post-tensioned concrete bridge cantilever wings. CFRP rods were selected as a direct parallel to PT steel bars owing to CFRP's superior fatigue, corrosion resistance, and lightweight properties as a composite material. The mechanical strengthening system is a metal anchor comprised of a stainless-steel barrel and split aluminum wedges in direct contact with a CFRP rod. The system strictly relies on friction for load-bearing capacity with no adhesives required. The developed CFRP mechanical anchorage system is assessed experimentally as part of a broader experimental program seeking to adequately transfer the CFRP post-tensioning force through bearing at anchorage ends to strengthen PT concrete bridge cantilever wing specimens that exhibit deterioration. The CFRP rods for strengthening will be embedded in near-surface-mounted (NSM) grooves in the negative moment region of the experimental PT concrete bridge cantilever wing specimens. The anchor features a contoured longitudinal profile consisting of a 1650 mm circular radius to minimize the stress concentrators at the loading end of the anchor, pushing the stress toward the back of the anchor. The anchor also features a competitive 80 mm in length stainless steel barrel and 80 mm in length aluminum wedge core. 7 specimens in total was carried out for the experimental assessment of the anchorage system. All prepared specimens measured 6 ft (1.80 m) in total length with a 5 ft (1.50 m) CFRP rod free gauge length in-between the ends of the anchors. 2 specimens as proof-of-concept anchorage testing was carried out with no pre-setting load to observe the behaviour of the design concept during loose wedge conditions. Subsequently, official anchorage static testing was carried out with 5 prepared specimens. 2 distinct pre-setting loads were selected to induce initial contact pressure between the wedges and the CFRP rod to reduce slippage. 3 specimens were pre-set at 80 kN and 2 specimens were pre-set at 100 kN before tensioning. The average ultimate capacity of the anchorage system was 97.58 kN, yielding a system efficacy of 63.4% against a guaranteed CFRP tensile strength of 154 kN. Adhering to the Canadian Highway Bridge Design Code, S6-19, the CFRP rods will be post-tensioned up to an effective jacking force of 45 kN at transfer due to the influence of the developed anchorage system.

1 Introduction

Bridge replacement is expensive; the US Federal Highway Administration (FHWA) has estimated that, in 2016, the total cost for the replacement of all structurally deficient highway bridges is more than 47 billion dollars (FHWA 2016). Thus, it is economically viable and eco-conscious to develop efficient strengthening systems to rehabilitate existing deteriorated bridges to achieve bridge service life. Strengthening structurally deficient highway bridges results in life cycle economic savings, reduction of negative environmental impacts, and limits traffic detours. Currently, several Departments of Transportation have found compromised transverse post-tensioning steel in bridge cantilever wings requiring a cost-effective rehabilitation strategy to maintain the service life of the bridge structure. Historically and currently, high-strength steel has been utilized for post-tensioning applications for concrete bridges, but harsh ambient environments which include constant freeze and thaw cycles, de-icing salts, de-icing chemicals, and exposure to marine air have reduced the service life of existing public infrastructure. Steel is susceptible to corrosion when in contact or exposed to oxygen and water. Harsh environments and climate change have facilitated an increased haven for the effects of corrosion. Over time as the steel is exposed to the elements, the steel rusts and loses its cross-section, which results in spalled concrete and a reduced structural capacity.

Prestressing steel applications have become a gold standard and common approach for the design of larger span to depth ratios in concrete members and the design of a multitude of concrete members including but not limited to bridge decks, bridge piers, and commercial malls slabs, ground applications, etc. Steel is isotropic and offers great ductility due to its great post-yielding plastic hardening properties. The major concern with steel that has led to investment in FRP materials is the issues regarding fatigue relaxation and corrosion. CFRP material is an alternative to supplement steel, but it has its Achilles Heel. Due to CFRP material's orthotropic properties, reduced ductility, and reduced ability to withstand sharp stress concentrators, conventional mechanical anchors used for post-tensioning steel strand applications are not suitable. A modification to existing mechanical anchorages is required to better suit CFRP. CFRP is weak in the transverse direction and cannot handle orthogonal compression as greatly as isotropic steel strands. However, when there are concerns related to the long-term durability of prestressed steel in terms of corrosion, fatigue, and relaxation, CFRP materials are a good candidate. CFRP is known for its high strength to weight ratio, non-corrosiveness, high durability, and high stiffness offering improved ultimate limit state and serviceability conditions for bridge infrastructure. Unlike conventional steel strands and bars, to the best knowledge of the authors, there are no available commercial anchorage systems for CFRP rods. Various researchers have experimented with bonded versus mechanical anchorage systems for CFRP materials. However, a mechanical strengthening system is more suitable for heavy civil infrastructure projects. The main concern with mechanical anchorage systems is how to adequately grip the CFRP rod without premature failure. Various experiments have been conducted in the past 2 decades with differential angles, contoured longitudinal profiles, and different geometry configurations for an optimum mechanical anchorage system. The contact pressure distribution on the rod surface plays a significant role in controlling the level of tensile loading that can be carried by the CFRP anchorage system. High contact pressure on the rod surface combined with high applied tensile stress induces premature failure due to the stress concentration at the loading end of the anchor. On the other hand, low contact pressure on the rod surface causes it to slip as the tensile load increases. Thus, a balance between contact pressure and tensile load capacity would provide for the ideal anchorage system. Optimum contact pressure is needed for a suitable anchor design to ensure no slippage as required by design codes. The contact pressure can be controlled by the profile geometry and the mechanical properties of the anchor components that are in direct contact with the CFRP rod. The competitiveness of a CFRP anchorage system would be to achieve a minimal anchor barrel and wedge length that is adequate to compete with conventional mechanical systems that grip steel strands. In this paper, a mechanical anchorage system is developed and experimentally assessed using 10 mm pultruded CFRP rods. ASTM D7205 FRP tensile tests are conducted on the CFRP rods in addition to proof-of-concept anchorage testing and official anchorage static testing. The purpose of the anchorage experimental testing is to use the developed anchor for experimental strengthening of half-scale PT bridge cantilever wing slabs.

2 Experimental Program

A novel mechanical anchorage system was developed, computer numerical control (CNC) machined, and assessed experimentally to evaluate its suitability and efficacy for the strengthening of post-tensioned concrete bridge cantilever wing slabs exhibiting deteriorated transverse steel post-tensioning. The developed CFRP mechanical anchorage system in this research study is a combination/adaptation from a combination of previous researchers including Al-Mayah et al (2006), Schmidt et al (2010, 2011), and Heydarinouri et al (2021). The experimental program consists of firstly, conducting tensile tests on the selected NO.3 (10 mm) CFRP rod as per the ASTM D7205-21 standard to verify the material properties of the CFRP rod. Secondly, conducting preliminary proof of concept testing to verify the design concept in-house. Lastly, conducting official static anchorage testing on the anchors per a specified load-controlled loading protocol. The goal of the proposed anchorage system is to provide effective means to jack and grip the CFRP rod up to a specified post-tensioning force in order to near-surface mount for strengthening post-tensioned concrete bridge cantilever wing slabs. This paper presents the details regarding the development and assessment of the proposed CFRP mechanical anchorage system. The presentation of the performance and behavior of post-tensioned concrete cantilever specimens that have undergone strengthening with NSM post-tensioned CFRP rods using the proposed mechanical anchorage system are outside the scope of this paper and will be addressed in another research paper.

2.1 Anchorage Design and Materials

The proposed mechanical anchorage system is based on existing mechanical anchorage systems used for conventional unbonded steel strand post-tensioning systems. The conventional anchorage design is modified and altered to apply to CFRP rods. In this research study, the proposed CFRP anchor is comprised of a barrel and split wedge system with a contoured longitudinal profile. The outer surface profile of the split wedges and the inner surface profile of the barrel is CNC machined with the same selected longitudinal circular radius of 1650 mm. The wedges are in direct contact with the CFRP rod and grip the rod relying purely on frictional resistance for load-bearing capacity. The wedges are housed inside a conical barrel that transfers the PT force to the to be strengthened concrete structure via a steel bearing plate. The main design concept of this anchorage system is the utilization of a contoured longitudinal profile within the anchor to prevent premature rupture of the CFRP from the stress concentrators at the loaded end of the anchor. The contoured longitudinal profile (LP) provides a distribution of the differential angles along the anchor, thus facilitating a balance between required contact pressure and the imparted high applied tensile stress concentration. Figure 1 depicts the design concept of the contoured longitudinal profile utilized in the current proposed CFRP anchorage system.

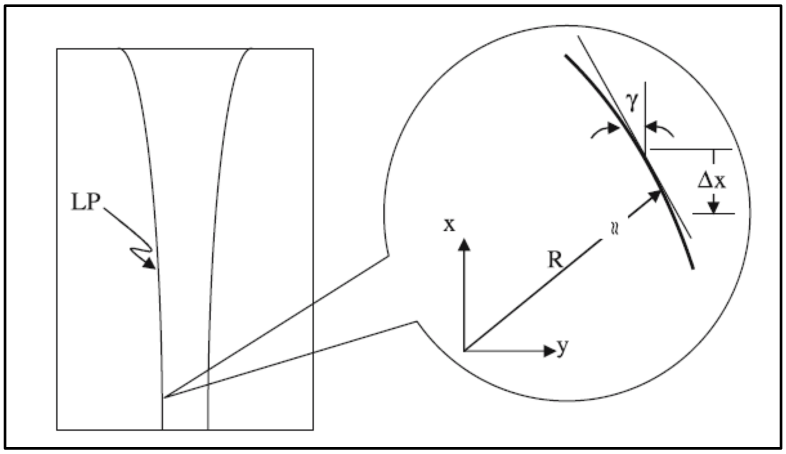

Figure 1: Anchor Contoured Longitudinal Profile (Obtained from Al-Mayah et al, 2006)

The CFRP material chosen for this research study is a unidirectional pultruded NO.3 (10 mm) CFRP Rod. Table 1 portrays the material properties of the selected CFRP rod.

Table 1: CFRP Rod Material Properties

Nominal Diameter (mm)	Cross Section Area (mm2)	Yield Strength (MPa)	Ultimate Strength (MPa)	Modulus of Elasticity (GPa)
10	71.26	N.A*	2172	124

*Not Applicable

Material selection for the anchorage components was based on the criteria of utilizing cost-effective, locally sourced, commercially available corrosion-resistant materials. Table 2 portrays the selected materials for the barrel and wedge components of the anchorage system.

Table 2: Anchorage Constituent Materials

Anchorage Component	Material
Barrel	Stainless Steel 316
Wedges	Aluminum 6061

Stainless Steel 316 was selected as the constituent material for the barrel for its exceptionally high resistance in chloride environments and overall corrosion-resistant properties. 316 is the most corrosion-resistant grade of stainless steel commercially available locally. Aluminum 6061 was selected as the constituent material for the split wedges for its low-cost, corrosion resistance, and great formability as a soft metal. The phenomenon of the plasticization of aluminum as the contact pressure increases results in the aluminum wedges conforming to the shape of the CFRP rod which increases the grip and friction between the wedges and rod resulting in a higher anchorage system tensile load capacity. Table 3 portrays the material properties of the selected anchorage components.

Table 3: Anchorage Material Properties

Material	Tensile Strength (ksi)	Tensile Strength (MPa)	Modulus of Elasticity (ksi)	Modulus of Elasticity (GPa)
Stainless Steel 316 Barrel	75	515	28,000	193
Aluminum 6061 Wedges	45	310	10,000	68

For CFRP mechanical anchorage systems to be competitive with existing steel strand post-tensioning anchorage systems, the barrel, and wedge lengths need to be as minimal as adequately possible. The length of the barrel and wedges of the developed anchor is similar to the anchorage system developed by Heydarinouri et al (2021). Figure 2 portrays the geometric details of the developed split wedge and barrel CFRP anchorage system.

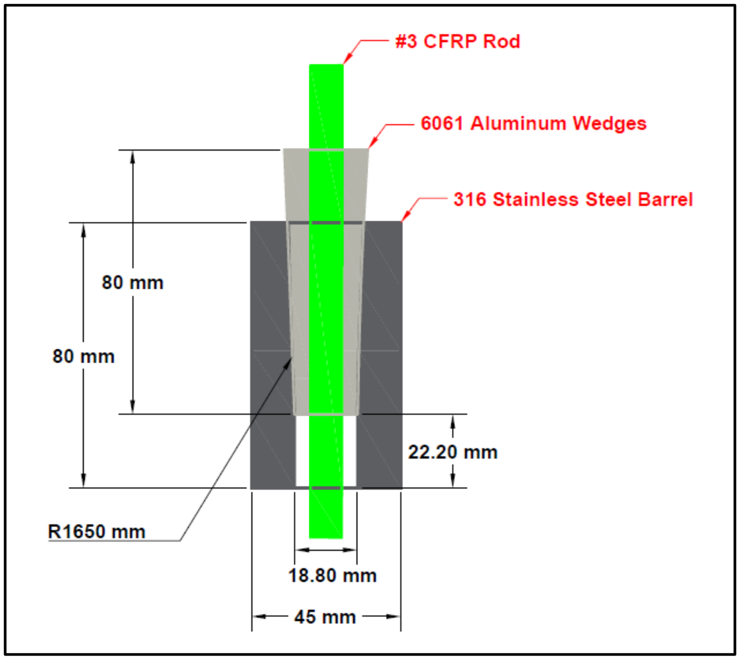

Figure 2: Split Wedge and Barrel Anchor Geometric Details

Figure 3 portrays the cross-section of the developed split wedge and barrel CFRP anchorage system.

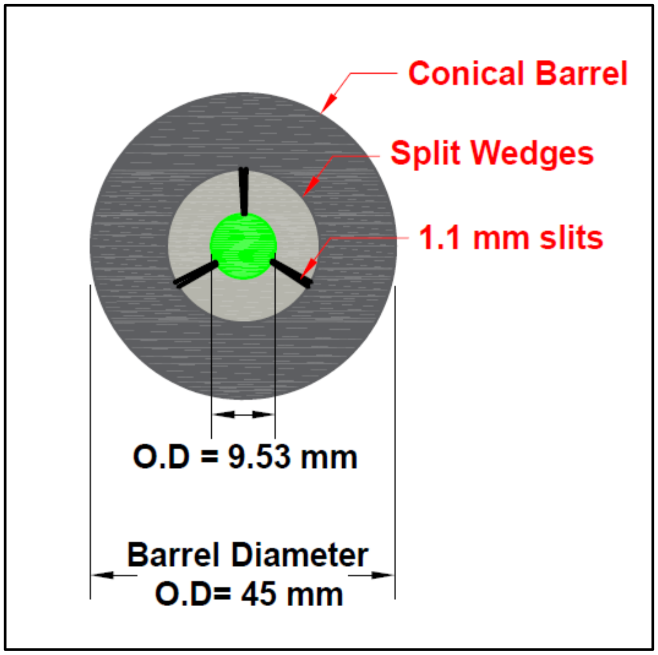

Figure 3: Split Wedge and Barrel Anchor Cross Section

2.2 ASTM D7205 FRP Tensile Tests

The tensile strength of the CFRP specimens was verified by following the ASTM D7205-21 standard. This test method determines the quasi-static longitudinal tensile strength and elongation properties of fiber-reinforced polymer matrix (FRP) composite bars commonly used as tensile elements in reinforced, prestressed, or post-tensioned concrete. This test method was chosen as an internationally recognized testing strategy to verify the material properties of the sourced CFRP rod and to cross-check with the manufacturer's reported values.

2.2.1 Test Matrix and Fabrication

The number of prepared specimens, specimen length, and CFRP free gauge length in-between the ends of the anchors were in adherence to the ASTM D7205-21 standard requirements. 5 specimens were prepared, and Table 4 portrays the observed test matrix.

Table 4: ASTM D7205 Tensile Test Matrix

Specimen ID	Material	Anchor Type	Specimen Length (m)	Specimen Length (ft)
S1	#3 CFRP Rod	Epoxy Potted Steel Pipe	1.80	6.0
S2	#3 CFRP Rod	Epoxy Potted Steel Pipe	1.80	6.0
S3	#3 CFRP Rod	Epoxy Potted Steel Pipe	1.80	6.0
S4	#3 CFRP Rod	Epoxy Potted Steel Pipe	1.80	6.0
S5	#3 CFRP Rod	Epoxy Potted Steel Pipe	1.80	6.0

To observe the ultimate strength of the CFRP rod in which the CFRP rod ruptures within its free gauge length, potted anchors were utilized as a gripping mechanism. Direct gripping of the CFRP rods by the jaws of the testing machine would result in premature failure. The anchors were comprised of ASTM A36 1¼" carbon steel schedule 80 pipes and an in-house developed epoxy resin with silica sand filler matrix as the potting material. Each specimen was 6.0 ft (1.80 m) in total length. Each anchor was 22" (550 mm) in length. The free gauge length of the CFRP rod in between the steel pipe anchors was 26" (650 mm). Two 350-ohm strain gauges were attached at the midpoint of the CFRP rod's free gauge length. Figure 4 portrays a schematic of the fabricated ASTM specimens for tensile strength testing.

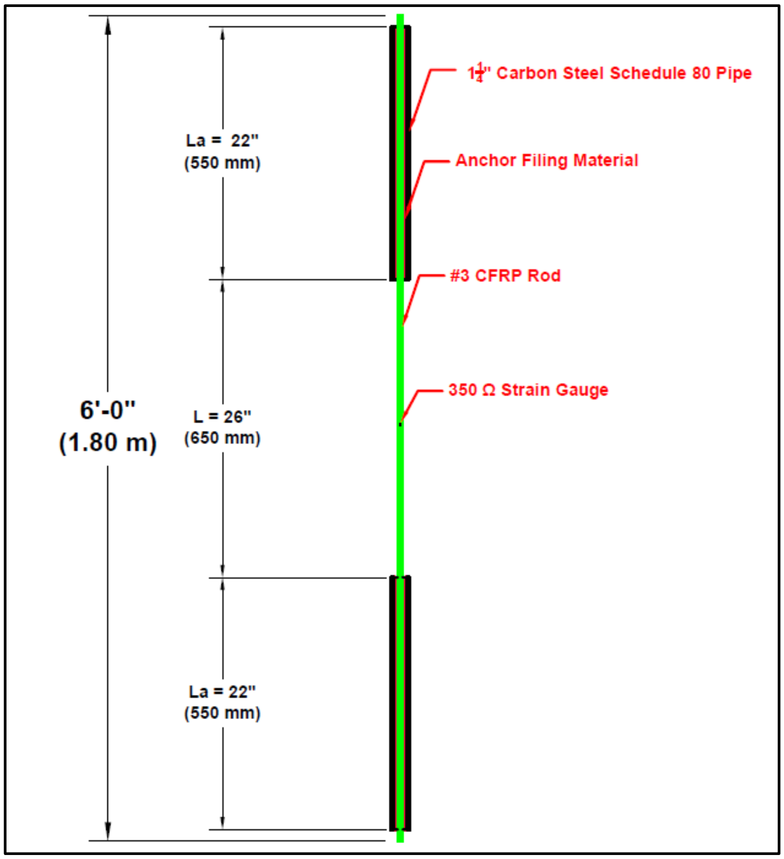

Figure 4: ASTM D7205 Tensile Test Specimen

Figure 5 portrays the cross-section of the steel pipe anchors inclusive of the steel pipe, the potting material, and the concentric CFRP rod.

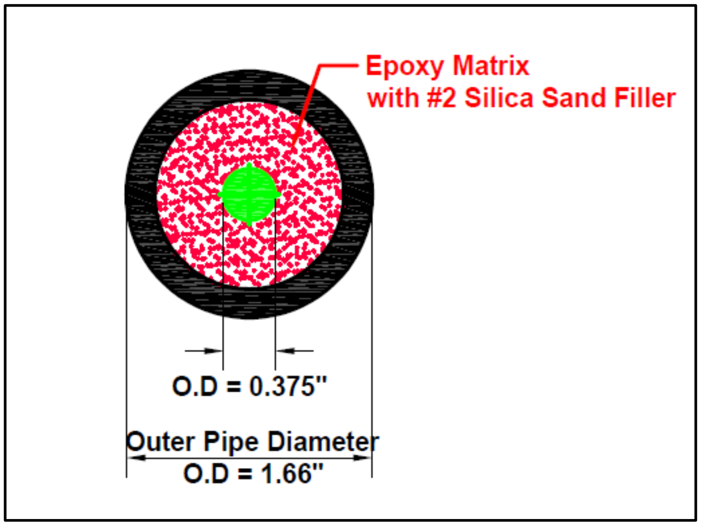

Figure 5: ASTM D7205 Tensile Test Specimen Cross-Section

A wooden jig from ¾” plywood was built to align the fabricated specimens. Alignment of the CFRP rod within the potted anchors is required to facilitate a pure tensile test with no induced bending. Figure 6 portrays the aligning jig built for the ASTM tensile tests.

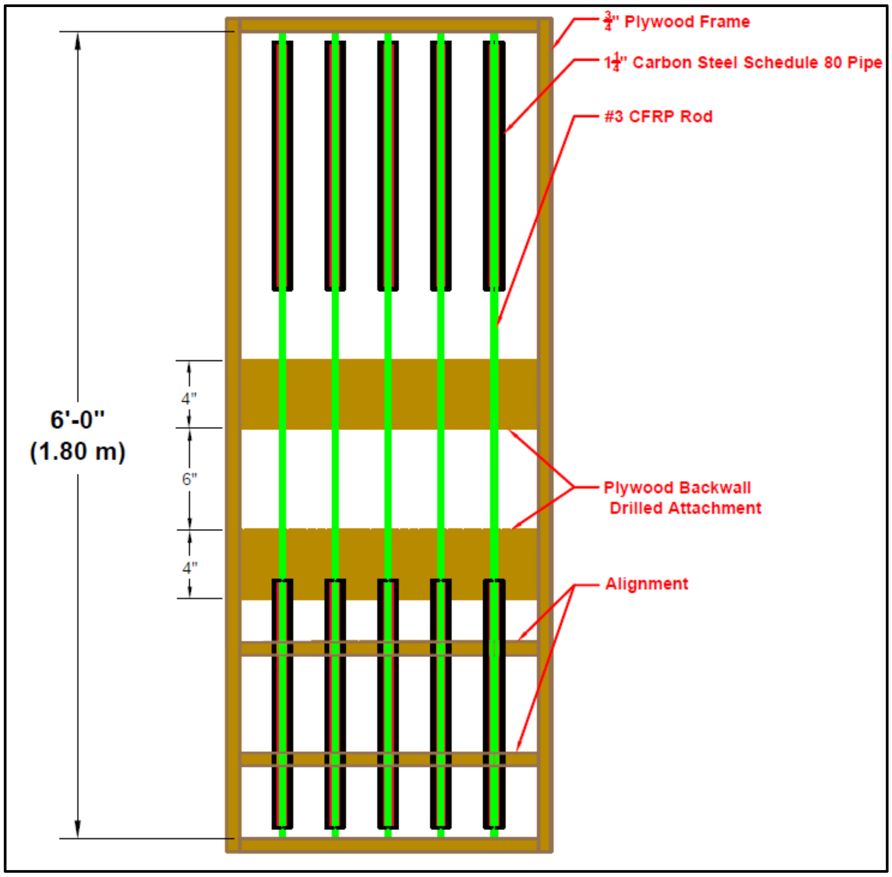

Figure 6: Jig for Aligning ASTM Specimens and Anchors

Figure 7 portrays a cross-sectional view of the built alignment wooden jig showcasing all 5 steel pipe anchors.

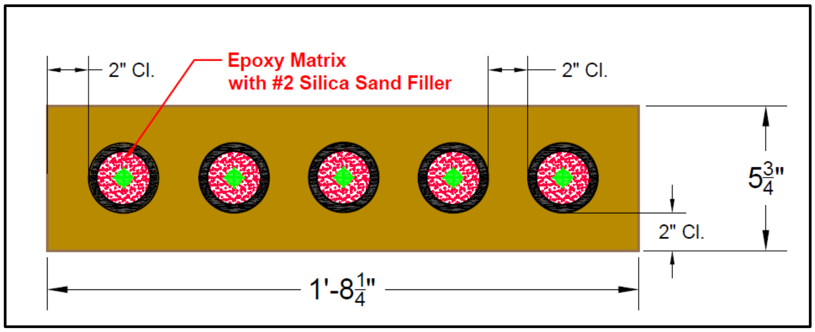

Figure 7: Cross-Section of Wooden Alignment

2.2.2 Test Results and Discussion

The 5 specimens were monotonically loaded using a displacement-controlled loading scheme of 2.5 mm/min until ultimate rupture. Table 5 portrays the results of the ASTM tensile tests.

Table 5: ASTM D7205 Ultimate Tensile Strength Results

Specimen ID	Ultimate Load (kN)	Ultimate Strength (MPa)
S1	193	2708
S2	193	2708
S3	191	2680
S4	175	2455
S5	163	2287

The obtained results verify that the CFRP rods meet the manufacturer's guaranteed tensile load of 154 kN and ultimate strength of 2172 MPa respectively.

2.3 Preliminary Mechanical Anchorage Tests

Preliminary proof of concept testing was conducted on the anchors to verify the proposed design concept of the contoured longitudinal profile, the geometric details portrayed in figure 2, and the selected materials for the respective components of the anchorage system.

2.3.1 Test Matrix and Fabrication

The purpose of the preliminary proof of concept tests was threefold. Firstly, to determine the suitability of the proposed anchor. Secondly, evaluate the behaviour and performance of each of the anchorage components. Thirdly, determine the overall efficiency of the anchor against the nominal strength of the CFRP rod. Ideally, the proposed anchor would be capable of developing the full ultimate tensile strength of the CFRP material with a rupture of the CFRP within its free gauge length. Since the application of the proposed CFRP anchorage system is intended for CFRP strengthening of a post-tensioned concrete bridge cantilever wing slab exhibiting deteriorated transverse steel post-tensioning in Canada, the Canadian Highway Bridge Design code will be utilized for code requirements. The Canadian Standards Association (CSA) S6-19 code, clause 16.8.6.3 on the capacity of FRP anchors stipulates that when tested in an unbonded condition, anchors for post-tensioning tendons shall be capable of developing a tendon force at least 50% higher than the jacking force. Thus, the test criteria for the anchor will be set to meet the CSA S6-19 bridge code. Additionally, after tensioning and seating, anchors shall sustain applied loads without slippage, distortion, or other changes that result in loss of prestress. The ultimate tensile capacity of the anchorage system and the displacements and slippage of the anchorage components will dictate the maximum permissible jacking force. 2 specimens were prepared for preliminary proof of concept testing. Table 6 portrays the proof-of-concept test matrix that was observed.

Table 6: Preliminary Proof of Concept Test Matrix

Specimen ID	Material	Anchor Type	Pre-Setting Load (kN)	Specimen Length (ft)	Specimen Length (m)
S1-Top	#3 CFRP Rod	Split Wedge & Barrel	None: Loose	6.0	1.80
S1-Bottom	#3 CFRP Rod	Split Wedge & Barrel	None: Loose		
S2-Top	#3 CFRP Rod	Split Wedge & Barrel	None: Loose	6.0	1.80
S2-Bottom	#3 CFRP Rod	Epoxy Potted Steel Pipe	None: Loose		

2 specimens were made for preliminary testing. No pre-setting load was applied onto the barrel anchors at this stage to observe the movements of the anchorage components at the loose state and to record when slippage occurs. The first specimen was comprised of a split wedge and barrel anchor for both the live and dead ends. The second specimen was comprised of a split wedge and barrel anchor for the live end and an epoxy potted steel anchor for the dead end. Both specimens were 6.0 ft (1.80 m) in total length with different free gauge lengths of CFRP rod owing to the longer length of the potted dead anchor. Figure 8 portrays a schematic of the fabrication of the preliminary proof of concept test specimens.

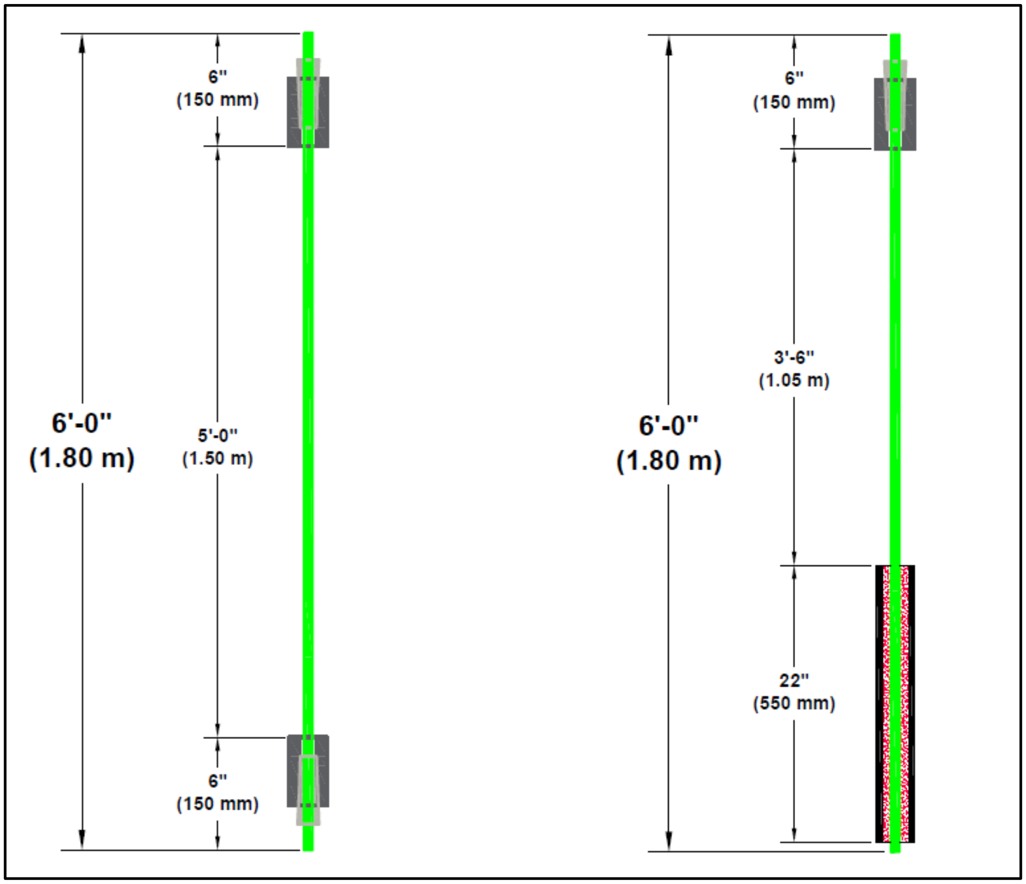

Figure 8: Preliminary Anchorage Static Test Specimens

The specimens were loaded based on a load-controlled stepwise loading protocol. The loading protocol was adapted from Rostasy 1998, and fib 1993. Table 7 portrays the stepwise loading protocol that was observed.

Table 7: CFRP Anchorage Test Loading Protocol

Load State	Load (kN)	Loading Rate (kN/min)	Load Step
20%	30	6	5 min Applied 5 min Sustained
40%	60	6	5 min Applied 5 min Sustained
60%	90	6	5 min Applied 5 min Sustained
70%	105	6	2.5 min Applied 60 min Sustained
100%	150	6	5-10 min Applied

The loading protocol portrayed in table 7 was chosen for the movements of the anchorage system components to be observed during stages of applied and sustained loading. The load-controlled stepwise loading protocol was understood as more advantageous than monotonic tensile loading until failure as it could capture the displacements of the anchorage components and is a better simulation of realistic periods of applied and sustained loading that bridge structures undergo. Linear potentiometers (LP) were placed on the top of the CFRP rod, the wedges, and the barrel to measure the draw-ins of each of the anchorage components as the tensile load increased. Figure 9 portrays the schematic for placement of the LPs on the anchorage components for draw-in measurements.

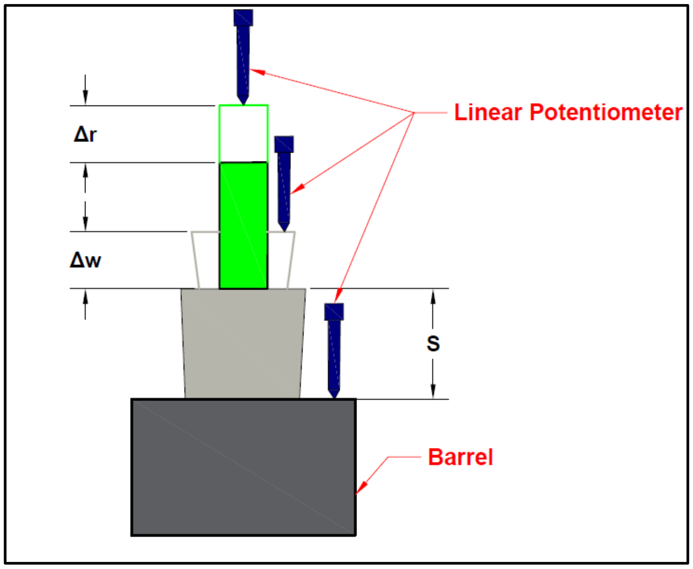

Figure 9: Anchorage Components Draw-in Measurements

2.3.2 Test Results and Discussion

The results of the preliminary proof of concept tests were promising to permit the continuation of the proposed anchorage design and geometric details. The proposed anchorage system was a good preliminary candidate worthwhile pursuing more tests and improvements. Table 8 portrays a summary of the preliminary proof of concept test results.

Table 8: Preliminary CFRP Proof of Concept Test Results

Specimen	Load (kN)	Failure Mode	Slippage	Efficacy (%)
S1	100.3	Pinching shear failure near the anchor	Observed around 10 kN	65
S2	102.7	Pinching shear failure near the anchor	Observed around 15 kN	66

Observing and recording the experimental preliminary anchorage tests yielded many learned lessons. The following points indicate the steps that were undertaken to improve the anchorage design before conducting the official anchorage static tests:

- Pre-setting the wedges to the required load to activate the system, increase the contact pressure around the CFRP rod, reduce slippage and overcome wedge seating losses rather than have loose wedges with no pre-setting.
- Arranging the 3 split wedges evenly around the CFRP Rod to ensure a uniformly distributed contact pressure on the CFRP rod.
- Application of metal-free anti-seize lubricant on the outer surface of the aluminum wedges to facilitate better insertion into the barrel and reduce any potential metal galling.
- Rounding off the tips of the wedges to reduce any sharp corners to reduce stress concentrators in the region of high shear and tensile stress.
- Threading of the barrels so a hex nut can thread onto the free end of the barrel to lock the jacking force being transferred to the bridge cantilever concrete specimens from the PT CFRP rod.

2.4 Official Mechanical Anchorage Static Tests

Official mechanical anchorage static testing was conducted to evaluate the short-term performance of the proposed CFRP anchorage system under short-term applied and sustained loads. The capacity and efficacy of the anchors were determined in addition to the draw-in measurements of the anchorage components as the tensile load increased.

2.4.1 Test Matrix and Fabrication

5 specimens were prepared for official experimental anchorage static testing. The specimens were pre-set vertically using an Instron machine. 3 specimens were pre-set at a load of 80 kN and 2 specimens were pre-set at a load of 100 kN. The 5 specimens were 6.0 ft (1.80 m) in length utilizing split wedge and barrel anchors for both the live and dead ends. A schematic of the fabrication of the specimens would be similar to the preliminary specimen, S1 in figure 7. Table 9 portrays the test matrix for the official anchorage static testing.

Table 9: Official Anchor Static Test Matrix

Specimen ID	Material	Anchor Type	Pre-Setting Load (kN)	Specimen Length (ft)	Specimen Length (m)
S1	#3 CFRP Rod	Split Wedge & Barrel	80	6.0	1.80
S2	#3 CFRP Rod	Split Wedge & Barrel	80	6.0	1.80
S3	#3 CFRP Rod	Split Wedge & Barrel	80	6.0	1.80
S4	#3 CFRP Rod	Split Wedge & Barrel	100	6.0	1.80
S5	#3 CFRP Rod	Split Wedge & Barrel	100	6.0	1.80

2.4.2 Test Results and Discussion

Table 10 portrays the ultimate tensile load capacity of the CFRP anchorage system, the load level where slippage was observed, and the efficacy of the anchorage system.

Table 10: Official CFRP Anchor Static Test Results

Specimen	Pre-Setting Load (kN)	Load (kN)	Observed Slippage	Efficacy (%)
S1	80	87.36	Around 70 kN	56.8
S2	80	98.89	Around 70 kN	64.3
S3	80	105.96	Around 70 kN	68.9
S4	100	97.67	Around 80 kN	63.5
S5	100	90.28	Around 80 kN	58.7

The average ultimate capacity of the anchorage system was 97.58 kN yielding a system efficacy of 63.4% against a guaranteed CFRP tensile strength of 154 kN.

2.5 Final CFRP Anchorage Design

Based on the results of the preliminary proof of concept and the official anchorage static tests that were conducted, the proposed split wedge and barrel CFRP mechanical anchorage system will be utilized for the strengthening of half-scale post-tensioned concrete bridge cantilever wing specimens exhibiting deterioration in the steel PT. Table 11 portrays the materials for the finalized CFRP anchorage design.

Table 11: Final CFRP Anchorage Materials

Anchorage Component	Material
Barrel	Stainless Steel 316
Wedges	Aluminum 6061
Spacer Disc	Plastic
Hex Nut	Stainless Steel 316

The final proposed novel CFRP anchorage system features the following items:

- 316 Stainless Steel Barrel.
- 3 Split 6061 Aluminum Wedges.
- No sleeves or adhesives, pure frictional resistance.
- A longitudinal circular profile with a circular radius of 1650 mm was used for the inner conical hole of the barrel and the outer aluminum wedge core.
- Radial Plastic Spacer Disc.
- Fine Barrel Threading with 1” Thick 316 Stainless Steel Hex Nut at the loading end of the barrel.
- Pre-set live & dead-end anchors.

Figure 10 portrays the final CFRP anchorage system. The system is comprised of live and dead anchors bearing on steel bearing plates that would bear on the PT bridge cantilever concrete specimen.

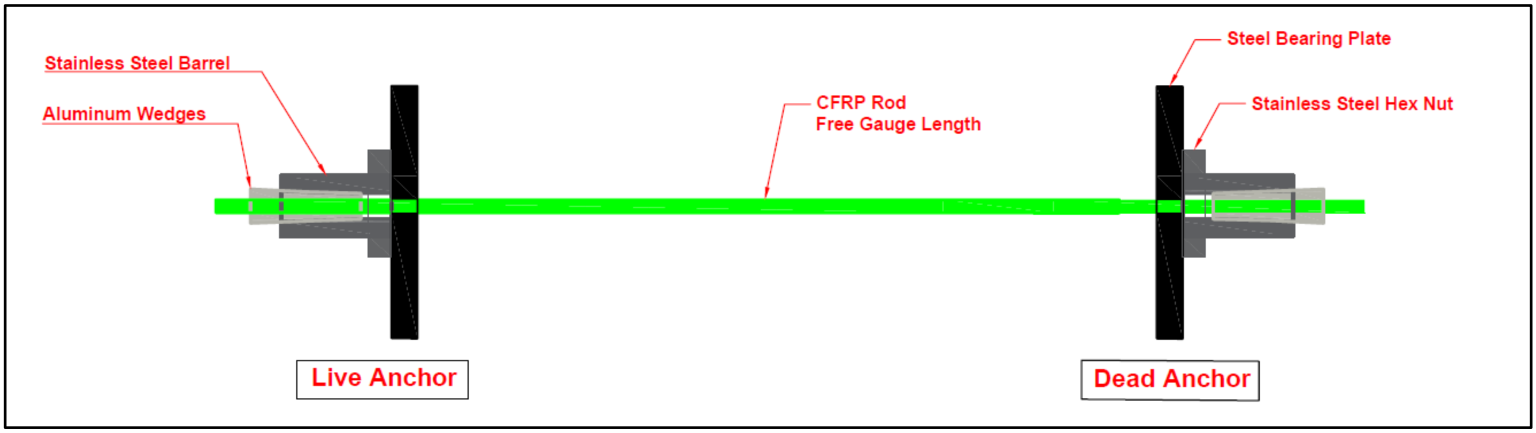

Figure 10: CFRP Anchorage Strengthening System

3 Conclusions

The results of the preliminary anchorage static tests showcased that the proposed CFRP anchorage system is promising for implementation to strengthen post-tensioned concrete bridge cantilever specimens up to a specified jacking force. In adherence to the Canadian Highway Bridge Design Code, the limitation of the effective post-tensioning force at transfer to concrete would be 45 kN. Although it would be highly advantageous and competitive for a mechanical anchorage system to not undergo pre-setting, slippage is prone to occur and was confirmed experimentally. The anchorage system in its loose stage where no pre-setting load is applied resulted in slippage at a very early tensile load. It was observed that no slippage occurred up to 70 kN when pre-setting to a load level of 80 kN. Also, no slippage occurred up to 80 kN when pre-setting to a load level of 100 kN. It was proven the CFRP anchorage system can be utilized further experimentally in strengthening PT concrete and that efforts are needed to improve the transverse modulus of the material to be more competitive with steel.

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