BOND OF PRESTRESSING STRANDS IN UHPC

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ABSTRACT

Ultra-High Performance Concrete (UHPC) has a reported compressive strength in the range of 200 MPa (29 ksi) to 800 MPa (120 ksi)[1] with the flexural bending strength being as high as 50 MPa (7 ksi)[2]. The relatively low flexural strength compared to the compressive strength of UHPC makes it a prime candidate for prestressing. However, a lack of experience in utilizing UHPC in bridge design leads to numerous questions. One of those questions concerns the bond between UHPC and prestressing strand.

Strands were cast into blocks of UHPC and pull-out tests were performed. A normal strength concrete sample served as a control specimen. The strands were not stressed and consisted of ½" and ½" oversized low relaxation grade 270 strands. Instrumentation was used to measure the applied load and the slip of the strand on the stressed end and free end. The results showed the UHPC to have superior bond capability compared to the control specimen.

Keywords: Ultra High Performance Concrete, Reactive Powder Concrete, Bond, Pull-out Tests, Prestressed Concrete.

INTRODUCTION

The technology of concrete has changed greatly in recent years. The changes have been the result of a better understanding of the microstructure of concrete. Ultra-High Performance Concrete (UHPC), is new material that is entering the construction industry. Typical large aggregate does not exist in UHPC. The maximum size of the coarse aggregate is typically 600 μm (20 mils)[3]. The compressive strength of UHPC has been reported in the range of 200 MPa (29 ksi) to 800 MPa (120 ksi)[1] with the flexural bending strength being as high as 50 MPa (7 ksi)[2]. The 800 MPa (120 ksi) UHPC requires a 400°C (750°F) dry heat while the 200 MPa (29 ksi) UHPC can be cured in a 90°C (200°F) moist environment. The relatively low flexural strength compared to the compressive strength of UHPC makes it a prime candidate for prestressing. However, a lack of experience in utilizing UHPC in bridge design leads to numerous questions. One of those questions concerns the bond between UHPC and prestressing strand. This bond is critical in transfer and development lengths, which affects the design and fabrication of prestressed members.

A test program was established to investigate the bond of UHPC to prestressing strands. Strands were cast into blocks of UHPC and pull-out tests were performed. A normal strength concrete sample served as a control specimen. The strands were not stressed and consisted of ½” and ½” oversized low relaxation grade 270 strands. Instrumentation was used to measure the applied load and the slip of the strand on the stressed end and free end. The results showed the UHPC to have superior bond capability compared to the control specimen.

BACKGROUND

Ultra high performance concrete (UHPC), also known as reactive powder concrete (RPC), is among one of the most recent innovations of Portland cement based materials that has been developed. With this recent innovation, high performance concretes (HPC) are no longer the strongest and most durable materials made with Portland cement. Table 1 compares some material properties of UHPC and HPC.

Table 1 – UHPC Compared With HPC

Material Characteristic	**UHPC compared with HPC**
Compressive Strength	2-3 times greater
Flexural Strength	2-6 times greater[1]
Elastic Modulus	1.5 times greater[4]
Total Porosity	4-6 times lower[2]
Microporosity	10-50 times lower[2]
Permeability	50 times lower[2]
Water Absorption	7 times lower[2,5]
Chlorine Ion Diffusion	25 times lower[2,5]
Abrasive Wear	2.5 times lower[5]
Corrosion Velocity	8 times lower[5]

UHPC CONSTITUENTS

The constituents of UHPC include Portland cement, silica fume, quartz powder (also referred to as quartz flour), sand, superplasticizer, water, and fibers. Each of the components in UHPC aids in optimizing the material properties, thus contributing to its extraordinary strength. Portland cement is the binder that holds this material together. When it reacts with water, it hardens through the process of hydration. Unfortunately, Portland cement actually hinders the minimalization of the porosity because when the water is added, the internal porosity of the cement increases. The cement particles range in size from 10-80µm.[4,6]

The density of the material is increased by using particles of specific sizes well spaced throughout the granular matrix. Spherical particles are preferable to maximize the packing capabilities of the mixture and to improve lubrication resulting in a less demanding mixing process. The spherical shape of silica fume fill voids between larger particles increasing the density and improve workability of the mix. The silica fume has an average diameter of 0.1-0.2µm.

Quartz powder or quartz flour is the reactive ingredient from which reactive powder concrete draws its name. For this reason, the crushed crystalline quartz powder is a vital ingredient in the mixture. The benefits of the quartz is that it is readily available and therefore relatively inexpensive, it is an excellent paste, and it is extremely hard. The quartz powder (or quartz flour) has an average diameter of 10-15µm.

The sand contributes the largest particle size in the matrix and the size of the sand particles is based on what will achieve the most optimal homogeneity. In UHPC, the particle size is limited to 600µm (0.024 inches) but no less than 150µm.[4] This fine sand can come from manufactured sand or from natural quarry sand. The more spherical shape natural sand demands less water and therefore is preferable.[4] Quartz sand presents advantages in that it is very hard, it is an excellent paste, and it is readily available.

One of the unique characteristics of ultra high performance concrete is the minimal amount of water used in the mixture sacrificing workability. Superplasticizer is needed to offset the flocculation caused by the electrical charges on the surface of the cement granules after grinding. The superplasticizer ratio must be high because of the minimal amount of water in the mixture.

The superior ductility of UHPC is attained through the incorporation of small steel fibers. Without the addition of the steel fibers, strength would be drawn from ionic forces making the material very brittle.[7] With the increased ductility, UHPC eliminates the need for temperature, shrinkage, and shear reinforcement[8] because the fibers reinforce the mix on a microscopic level. The size of the fibers integrated into the mixture is very important. For example, when steel fibers sized 0.008in (0.2mm) in diameter and 1.0in (25mm) long are added to the UHPC mixture, it would be like adding an 0.3in (8mm) diameter by 3.3ft (1m) reinforcing bar to regular concrete.[9] Other fibers, such as polypropolene, have been added to

UHPC for architectural and fire resistance purposes. Confining the material in metal tubes is the alternative to the steel fibers.

MIXING UHPC

The mixing process for UHPC is longer than the mixing procedure for conventional concrete. Additionally, accurate weighing devices are needed to get the correct amount of each component as variations can have an effect on the mechanical properties of the concrete. Production is easiest in a plant with a central pan mixer, however studies have shown that a ready mix truck can be used if necessary.[6,10]

Manufacturers of UHPC may deviate on the specifics of the mixing procedure for their particular product. Generally, the dry powders are mixed until a homogeneous mix is obtained which can take several minutes. Then a portion of the water and half of the superplasticizer are added as mixing continues. Several minutes later, the remaining water and superplasticizer are added. When the mix is fairly homogenous, the fibers are added.

HEAT/PRESSURE TREATMENT

Pressure and heat treatment are optional to enhance the performance of the material. The heat treatment for this concrete is implemented following the initial setting of the material. The heat treatment alters the microstructure, thus increasing the compressive strength.[2] Additionally, the durability properties are enhanced and there is virtually no shrinkage and very low creep. A number of variations on the specific temperature, humidity during the treatment, and the duration of the treatment have been evaluated in different reports.[1,4,11,12] The most commonly implemented heat treatment involves subjecting the specimen to 195^{o}F (90^{o}C) under very moist conditions for 48 hours. This treatment frequently results in compressive strengths 60 to 70 percent greater than untreated samples of the same mix composition.[2]

Pressure is applied during hardening to decrease the porosity of the mixture. The pressure counteracts increased porosity that occurs during the hydration of Portland cement. The effects of applied pressure are a reduction of entrapped air, removal of excess water, and compensation for chemical shrinkage.[4] All of these result in an increase of 5 percent relative density and a compressive strength increased by 70 percent.[2] The use of these additional techniques should be based on the requirements for the specific application.

COST

The price of UHPC is high, but is falling quickly. In 1996, one report estimated the price at approximately $400 per cubic yard (without steel fibers) and $1100 per cubic yard (with steel fibers),[10] but a 1999 report estimated the price at $500 per cubic yard (with steel fibers)[9]. For the purpose of comparison with steel, one ton of steel averages $700 and one ton of UHPC can cost between $300 and $500 depending on whether steel fibers are incorporated.[9] UHPC is more costly to produce than traditional concrete, but savings result from time saved during the design, less material for the same job, labor cost reductions, less maintenance and repair and a longer service life.[13] It is not anticipated that UHPC would compete with regular concrete, but rather, it is more likely to compete with steel.

RECENT RESEARCH AND APPLICATIONS

A UHPC bridge girder was tested by FHWA (Federal Highway Administration) in conjunction with the Virginia Department of Transportation (VDOT) in 2001.[14] The VDOT has been considering the use of ultra high performance concrete on bridge applications. The advantage of using UHPC in bridge girders would be the post cracking strength provided by the fibers in the matrix and the removal of mild reinforcement. An 80 foot (24.4 meters) AASHTO Type II prestressed UHPC girder was cast and after initial set, underwent a heat treatment in a vapor bath at 88°C (190°F) for two days. Three point flexural testing was performed on the girder by applying two loads 6 feet (1.8m) apart centered around the midpoint. The girder deflected 12 inches (30 centimeters) with no cracks and the load was held for 12 hours. The test was resumed and the girder deflected 19 inches (48 centimeters) before fracturing.[4] The peak applied moment was 3225 kip-feet (4,400,000 Nm) which corresponded to a peak applied load of 180 kip (800,000 N).[14] The shear test, performed at 6.5 feet (2.0 meters) from the support, revealed a shear strength of 380 kips (1,700,000 N).[12] The results prove that UHPC shows potential for use in bridge construction. However, it was determined through this study that more efficient shapes will need to be developed to allow the material to be used in a more practical manner in bridge design.

In 1997, the University of Sherbrooke conducted a test to investigate the practicality of using locally available materials and the possibility of using a ready mix truck for the mixing process.[10] The mix prepared by the ready mix truck was compared with a mix prepared in a pan mixer. Both used the same mixing sequence and were followed by a specific curing cycle. The mechanical properties of both mixes were comparable. The compressive strength for the UHPC mixed in the ready mix truck varied between 23,500 psi and 31,500 psi (163 and 217 MPa) while the UHPC prepared in a pan mixer had a compressive strength of 28,500 psi (197 MPa).[6] The results of this study revealed the capability to use local materials for the constituents of UHPC and the ability for these materials to be mixed in a ready mix truck.

The first major structural application of UHPC in the world was the Sherbrooke Footbridge completed in 1997 in Canada.[9] The bridge was designed to take advantage of the outstanding mechanical properties of this new material while exhibiting aesthetic possibilities, providing a very low maintenance structure, and setting up a research platform for the University of Sherbrooke. The bridge was designed to carry pedestrian and bicycle traffic. The bridge was constructed with UHPC confined and also unconfined. As this was the first major structure using UHPC, the full potential of the material was not exploited for reasons of safety. The bridge consisted of six web space truss sections spanning 197 feet (60 meters) over the Magog River in a circular arch shape with a radius of 1070 feet (326 meters). The sections were plant fabricated including a 48 hour heat treatment in hot water vapor, and assembled on site. The full depth of each segment including the web truss was 10 feet (3 meters). Each segment included two top and two bottom chords, the deck and several diagonal members. The material properties allowed for an extremely lightweight and sleek design with the deck 11 feet (3.3 meters) wide and a mere 1 $^3/_{16}$ inches (30 millimeters) thick. The top and bottom chords were composed of UHPC with a compressive strength of 29,000 psi (350 MPa).[8] The diagonal members were 6 inch (150 millimeter) diameter 10.5 feet (3.2 meter) long cylinders composed of UHPC confined in a $^1/_{16}$ inch (2 millimeter) thick stainless steel tubes.[8] These diagonal members could withstand 50,000 psi (350 MPa) in compression. To set up a research platform for the University of Sherbrooke, instrumentation was installed on the bridge to record temperature variations, measure strains, monitor deflections, measure loads in web members, record prestressing forces, and measure vibrations.[8]

The Footbridge of Peace, erected in 2001, in Seoul, South Korea is a more recent large-scale application of the use of UHPC.[3] The footbridge was a gift from France to the Republic of Korea in honor of the millennium celebration. This bridge was constructed using an elaboration of UHPC called Ductal manufactured by Bouygues in France in conjunction with LaFarge Corporation. This bridge spans 394 feet (120 meters) in six precast segments with no column support over the Han River. Each segment is 72 feet (22 meters) long, 4.25 feet deep (1.3 meters) with a deck 1 $^3/_{16}$ inches (3 centimeters) thick and 14 feet (4.3 meters) wide. The segments underwent a heat treatment at 200^{o}F (93^{o}C) for 48 hours following the initial setting. The wedge shaped segments were connected by six cables, three segments at a time, from the river banks toward the center, then the middle was cast in place to connect the two sides of the bridge. Unlike its predecessor, the Sherbrooke Footbridge, this bridge takes full advantage of the strength of the material.

BOND STRENGTH

Prestressing UHPC will take advantage of the relatively high compressive strength to tensile strength ratio of UHPC. The bond between UHPC and prestressing strands are important in determining transfer and development lengths. Due to the fact that UHPC has such drastically different mechanical properties as compared to conventional concrete, the previous methods for determining transfer length and embedment must be reevaluated.

EXPERIMENTAL PROCEDURE

TEST SAMPLES

A test program was established to investigate the bond of UHPC to prestressing strands. Strands were cast into blocks of UHPC and a normal strength concrete sample served as a control. The dimensions of the samples are summarized in Table 2.

Date Poured	Sample	Width in (m)	Height in (m)	Depth in (m)
7/10/2002	Conventional concrete	48 (1.22)	30 (0.76)	24 (0.61)
10/15/2002	UHPC#1	48 (1.22)	30 (0.76)	24 (0.61)
1/9/2003	UHPC#2	48 (1.22)	30 (0.76)	24 (0.61)
1/9/2003	UHPC#3	48 (1.22)	30 (0.76)	18 (0.46)
1/22/2003	UHPC#4	48 (1.22)	30 (0.76)	12 (0.30)

Table 2 - Test Samples

The strands were not stressed and consisted of ½” and ½” oversized low relaxation grade 270 strands. Two rows of four strands were cast into each sample. The strands were centered on the 48 inch (1.22 m) wide by 30 inch (0.76 m) high side of each sample and spaced 9” within each row and 9” between each row. The spacing between rows and strands within rows allowed for placement of a prestressing chair to perform the pull-out and reduced the amount of compression existing around the strands. The ½” strands were placed in the upper row and the ½” oversized strands were placed in the bottom row. The prestressing strands protruded at least 4 feet (1.22 meter) on one side and at least 1 foot (0.30 meter) on the other side of each sample. The 4 foot (1.22 meter) strand extension was the side of the sample that the pull-out force was applied and is referred to as the live end. This extension was necessary to allow space for the necessary testing equipment. The 1 foot (0.30 meter) strand extension side of the sample was not stressed is referred to as the dead end.

The UHPC samples were poured on different dates as shown in Table 2 at a precaster’s facility. The first UHPC pour was done to become familiar with mixing sequence of the UHPC and was done with the assistance of one of the UHPC manufacturer’s research technicians. The next pour occurred after preliminary results were obtained from pull-out testing of strands from UHPC#1. The final UHPC pour occurred due to problems with a form during the second pour.

Cylinders were cast during all pours and consisted of 3 inch (76.2 mm), 4 inch (101.6 mm), and 6 inch (152.4 mm) diameter specimens. In order to achieve a flat and level cylinder ends, the cylinders were first saw cut and then milled. This procedure was necessary because capping compound was not sufficiently strong to support the loads attained in testing the UHPC cylinders.

The pull-out samples were not heat treated due to facilities not being large enough to contain the samples and maintain the high temperature required for the heat treatment. However, cylinders from the first UHPC pour were heat treated to evaluate the effects of heat treatment. The 194°F (90°C) for 48 hours heat treatments applied to the cylinders consisted of a dry condition, a variable humidity with a high of 55 percent relative humidity, and a constant 95 percent relative humidity. All of the heat treatments were applied in the temperature and humidity chamber. Cylinders that did not undergo heat treatment remained next to the pull-out samples until testing.

TEST SETUP

The pull-out tests were performed in the same manner for both the conventional concrete block and the UHPC samples. A diagram showing the setup for the pull-out tests is shown in Figure 1. A prestressing chair was used to transfer and distribute the load to the block. Under the chair, a Linear Variable Differential Transformer (LVDT) was attached to the strand with a fabricated clamp. The core connecting rod of the LVDT was placed in contact with the sample. The LVDT was used to measure the distance that the strand moved on the live end. Behind the chair, a hollow hydraulic cylinder was positioned around the strand. The cylinder was followed by a load cell to monitor the load being applied. Specially fabricated plates were placed on each side of the load cell to disperse the load applied by the cylinder and to prevent damage to the load cell. Lastly, a prestressing strand chuck was placed over the strand to transfer the load from the hydraulic cylinder to the strands. On the dead end, another LVDT was clamped to the strand with the core connecting rod placed in contact with the sample. This LVDT measured any movement of the strand on the dead end. Specifically, the actual pull-out behavior and displacement, if any occurred, would be monitored with the dead end LVDT.

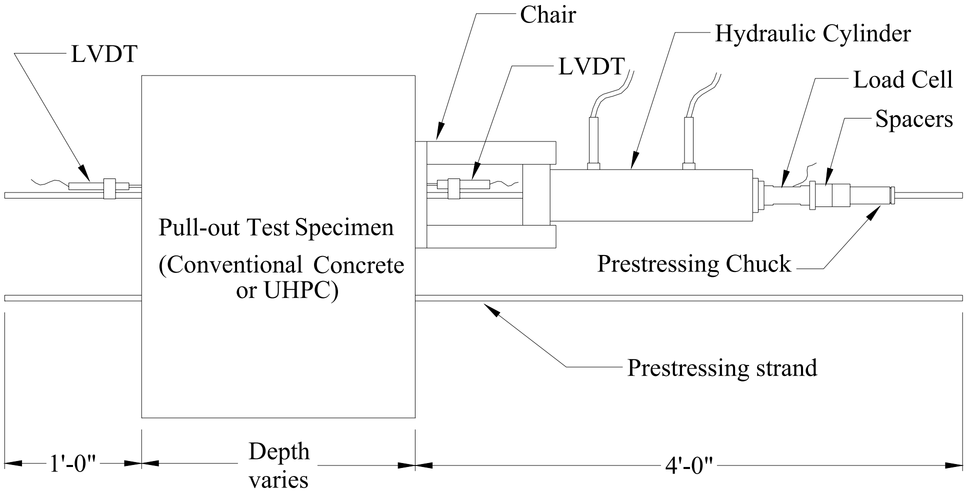

Fig. 1 - Pull-out Test Set-up

The LVDTs and the load cell were attached to a data acquisition system. The data acquisition system was connected to a laptop computer for the storage of data and. This allowed for the instantaneous display of the loads applied and the displacements occurring. . Once the readings for the LVDT on the dead end showed that pull-out had occurred, the test was stopped. The test setup of an actual sample is shown in Figure 2.

Fig. 2 - Pull-out Test Sample

RESULTS

COMPRESSIVE STENGTHS

Table 3 provides the results of the compression tests on the cylinders. The conventional concrete had an average compressive strength of 3.8 ksi (26 MPa). The average compressive strength of the first UHPC pour (UHPC#1) had a compressive strength of 21 ksi (144 MPa). The second UHPC pour (UHPC#2 and #3) had a compressive strength of 20 ksi (137 MPa). The third and final UHPC pour (UHPC#4) had a compressive strength of 19 ksi (131 MPa). The second and third UHPC pours were believed to have slightly lower strengths due to the cooler temperatures experienced during the pouring compared to the first UHPC pour. The cooler temperatures resulted in lower internal temperatures of the UHPC during curing as verified by thermal couples.

Table 3 also provides the results of the compression tests for the heat treatment applied to UHPC#1. As shown, the average compressive strength for the cylinders with only the heat and no applied humidity was approximately 26 ksi (179 MN/m^2). The average compressive strength for the cylinders with heat treatment and variable humidity was approximately 27 ksi (187 MN/m^2). The compressive strength for the cylinder with heat treatment and 95 percent relative humidity increased to approximately 28 ksi (191 MN/m^2).

Heat Treatment	Cylinder Number	Average Compressive Strength (psi)
No treatment	Conventional	3,848
	UHPC#1	21,163
	UHPC#2 / #3	19,982
	UHPC#4	19,320
90^{o}C dry for 48 hours	UHPC#1	25,932
90^{o}C and variable humidity for 48 hours	UHPC#1	27,104
90^{o}C and 95%RH for 48 hours	UHPC#1	27,768

Table 3 - Results of CylinderCompressive Strength Tests

PULL-OUT TEST RESULTS

The typical behavior of the pull-out tests for the conventional concrete is shown in Fig. 3. The strand end with the applied load (live end) initially exhibited a linear load/displacement relation. As the load increased, the relationship became nonlinear and a smaller load increase was necessary to increase the displacement of the strand. The strand end that was not loaded (dead end) initially exhibited minimal displacement until the load reached a significant magnitude, approximately 30 kips. As the load increased, the displacement of the strand's dead end increased nonlinearly. Finally, the magnitude of the load was significant enough to continually displace the strand without any increase and the bond between the strand and concrete was insignificant. The behavior of the pull-out tests for the half-inch oversized strands were very similar to the half-inch standard strands for the conventional concrete. No strands were broken during the pull-out tests of the conventional concrete sample.

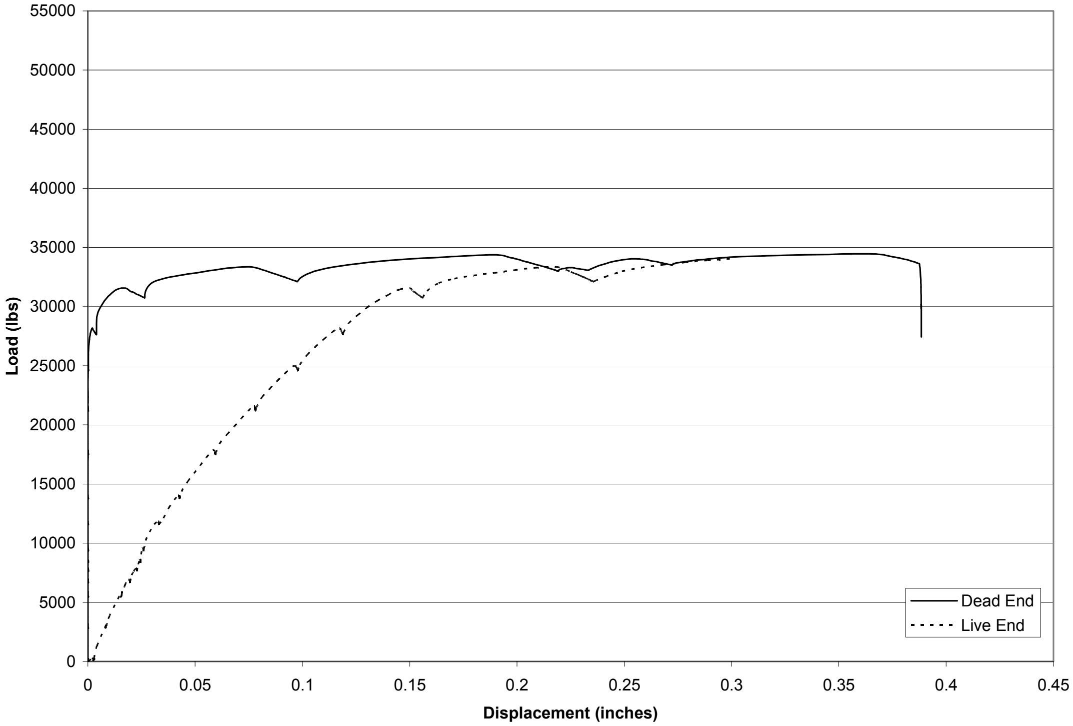

Fig. 3 - Typical Pull-Out Behavior from Conventional Concrete

Figure 4 shows typical pull-out test results for the standard ½” strands embedded in the UHPC#1 and #2 samples. The live end of the strand initially exhibited a linear load/displacement relation. As the load increased, the relationship became nonlinear and a smaller load increase was necessary to increase the displacement of the strand. The nonlinearity of the load/displacement curve was not as pronounced as the conventional concrete sample when considering the 24” (0.60 m) and 18” (0.4 m) UHPC samples (UHPC#1 - #3). The nonlinearity 6 mportion of the 12” (0.30 m) UHPC sample (UHPC#4) was more significant and comparable to the 24” (0.60 m) conventional concrete sample.

As shown in Figure 4, the dead end of the strand initially exhibited minimal displacement until the load reached a significant magnitude, approximately 32 kips, for UHPC #1 and #2. Displacement initiated at loads of approximately 24 kips and 20 kips for the dead ends of UHPC#3 and UHPC#4, respectively. As the load increased, the displacement of the strand’s dead end increased nearly linear for UHPC#1 - #3. The dead end of the strand for UHPC#4 exhibited a nonlinear load/displacement relation. The behavior of the pull-out tests for the half-inch oversized strands were very similar to the half-inch standard strands for the UHPC samples with an increase in the magnitude of the loading. All strands were fractured during the pull-out tests of UHPC samples before significant displacement at a constant load occurred.

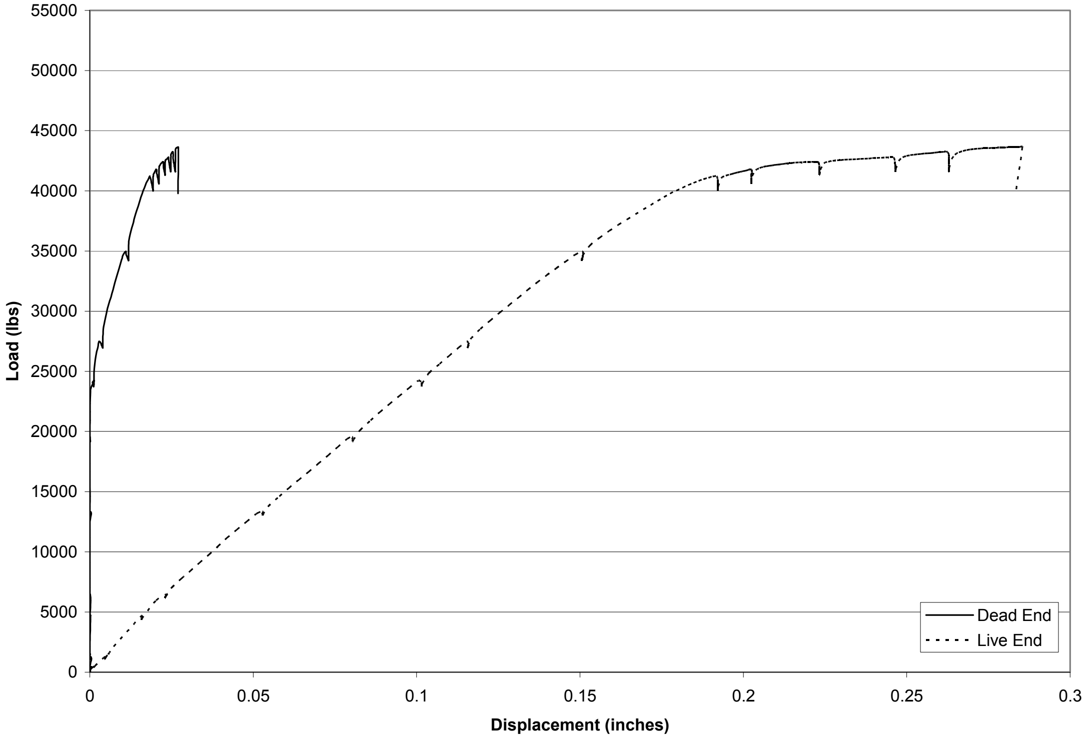

Fig. 4 - Typical Pull-Out Behavior of UHPC #1 and UHPC #2

A summary of the ½” strand pull-out tests is provided in Table 4. The table provides the average load and standard deviation of the tests for each sample at various dead end displacements. The average maximum displacements of the strand’s dead end are also provided in Table 4. Locations in the table without data are due to all the strands failing prior to the specified displacement or only one strand reaching the specified displacement making the standard deviation not applicable. The loads at similar dead end displacements for UHPC#1and #2 samples were significantly higher than the conventional concrete sample. In addition, all the strands in the UHPC#1 and #2 samples fractured prior to an increasing displacement with constant load. None of the strands in the conventional concrete sample fractured. Therefore, there was significant improvement in the bond of the UHPC compared to the conventional concrete when comparing similar embedments of 24”(0.60 m). UHPC#3 experienced lower load at small displacements and then had a higher load at displacements greater than approximately 0.01” (0.25 mm) than the conventional concrete sample. UHPC#4 experienced lower load at all displacements shown in Table 4 compared to the conventional concrete sample. However, all strands fractured for the UHPC#4 sample and resulted in a significantly lower maximum displacement compared to the conventional concrete sample.

A summary of the ½” oversized strand pull-out tests is provided in Table 5. The table is similar to Table 4 with higher magnitude loads. Table 5 shows the use of the oversized strand did not show much difference for the conventional concrete, but a significant increase was exhibited for the UHPC samples. Even UHPC#4 showed higher loads at displacements

Pour (depth of embedment)	Statistic	Load at Given Displacements (kips)					Maximum Dead End Displacement (in)
		0.002 in	0.005 in	0.01 in	0.02 in	0.03 in	
Conventional Concrete (24 in)	Avg	30.2	31.2	32.6	33.5	33.5	0.42729
	St.Dev.	1.6	1.9	1.4	1.9	1.7	0.09940
UHPC #1 (24 in)	Avg	32.1	38.1	40.7	45.5	---	0.01518
	St.Dev.	4.8	6.7	4.1	---	---	0.00810
UHPC #2 (24 in)	Avg	32.6	34.9	36.2	40.3	42.1	0.02399
	St.Dev.	6.4	6.1	2.9	1.4	---	0.01399
UHPC #3 (18 in)	Avg	24.1	28.4	31.9	38.1	42.1	0.03803
	St.Dev.	2.8	2.2	2.4	2.7	2.2	0.00939
UHPC #4 (12 in)	Avg	20.6	22.6	24.8	28.8	31.3	0.14917
	St.Dev.	2.0	2.4	3.0	3.2	3.9	0.07854

Table 4 - Pull-Out Test Results for ½" Strands

greater than approximately 0.01" (0.25 mm) compared to the conventional concrete sample. All strands fractured in the UHPC samples prior to significant pull-out displacement and resulted in much lower maximum dead end displacements than the conventional concrete sample.

Pour (depth of embedment)	Strand Number	Load at Given Displacements (kips)					Maximum Dead End Displacement (in)
		0.002 in	0.005 in	0.01 in	0.02 in	0.03 in	
Conventional Concrete (24 in)	Avg	29.5	30.4	30.9	32.1	32.3	0.21968
	St.Dev.	1.9	3.2	1.9	2.2	2.8	0.14331
UHPC #1 (24 in)	Avg	43.0	45.1	---	---	---	0.00449
	St.Dev.	4.6	---	---	---	---	0.00344
UHPC #2 (24 in)	Avg	43.1	44.4	45.8	46.9	---	0.00716
	St.Dev.	---	---	---	---	---	0.00998
UHPC #3 (18 in)	Avg	37.9	41.8	43.7	45.7	46.6	0.01588
	St.Dev.	3.1	0.7	0.8	---	---	0.01182
UHPC #4 (12 in)	Avg	26.2	28.7	32.5	36.5	39.3	0.12069
	St.Dev.	3.7	3.1	3.7	2.9	2.0	0.04891

Table 5 - Pull-Out Test Results for ½" Oversized Strands

CONCLUSIONS

The results of this study showed that applying heat treatment to the UHPC had a significant impact on increasing the compressive strength of the material. A heat treatment with 95% relative humidity provided the best results, but heat treatment even in a dry environment is beneficial.

The pull-out tests performed in this study showed that the bond of UHPC to unstressed ½” and ½” oversized prestressing strands to be significant compared to a 3.8 ksi conventional concrete. A strand embedment of only 12” (0.30 m) into the UHPC resulted in fracture of the strands during pull-out tests before any significant displacement of the strand occurred.

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