FABRICATION OF AN OPTIMIZED UHPC BRIDGE

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ABSTRACT

The Federal Highway Administration's ongoing research program investigating the use of Ultra-High Performance Concrete (UHPC) in highway bridges is now focusing on the optimal structural use of UHPC in bridge girders. Structural optimization of prestressed concrete bridge girders for use with UHPC has been completed. The resulting cross-section is a bulbed double-tee shape with thin webs and a 3 inch thick deck. The girder is 70 feet long and 33 inches deep, has an 8 foot wide deck, and weighs 23 tons. The cross-section contains 24 prestressing strands and no mild steel. Four of these girders have been constructed using a 28 ksi compressive strength, steel-fiber reinforced UHPC.

Construction of a bridge using two of these girders is underway at the Turner-Fairbank Highway Research Center. This bridge will be periodically tested and monitored for several years. The remaining two girders will be destructively tested to determine a baseline behavior for this material/girder combination.

Although this bridge girder design is not expected to become widely used in the bridge industry, the fabrication of these girders has made it possible to identify and resolve some potential obstacles to implementation. Solutions to some difficulties encountered during the fabrication process are discussed.

Keywords: Ultra-High Performance Concrete**,** UHPC, Optimized Cross-Section, Double-Tee, Prestressed Girder, Fabrication, Steel Fiber

INTRODUCTION

The Federal Highway Administration's ongoing research program investigating the use of Ultra-High Performance Concrete (UHPC) in highway bridges is now focusing on the optimal structural use of UHPC in bridge girders. The advanced properties exhibited by UHPC are well suited to use in prestressed concrete bridge girders, particularly decked girders. This paper discusses the fabrication of four full-scale optimized girders from design through construction.

ULTRA-HIGH PERFORMANCE CONCRETE

UHPC is a new class of concrete that exhibits significantly enhanced strength and durability properties as compared to normal and high-performance concretes. In general, UHPC is a steel fiber reinforced concrete consisting of an optimized gradation of fine powders and a very low water to cementitious materials ratio. Two of the primary sources for the enhanced material behaviors are the finely graded and tightly packed nature of the concrete constituent materials and the steel fibers which knit the material together after cracking has occurred.[1-4]

There is currently one UHPC widely available in the United States. It is being marketed by Lafarge, Inc. under the name Ductal®. Although it is a proprietary material, general constituent material and mix proportion information is available. Table 1 provides the material composition. The steel fibers are 0.5 inch long, 0.08 inch diameter undeformed steel wires included in the mix in the proportion of 2 percent by volume. The largest aggregate in the mix is a fine sand with a maximum size of 0.024 inches. The water to cementitious materials ratio is less than 0.20.

Table 1. UHPC Composition.

Material	Amount (lb/yd^3)	Percent by Weight
Portland Cement	1200	28.5
Fine Sand	1720	40.8
Silica Fume	390	9.3
Ground Quartz	355	8.4
Superplasticizer	51.8	1.2
Accelerator	50.5	1.2
Steel Fibers	263	6.2
Water	184	4.4

In association with the research that is the topic of this paper, the Federal Highway Administration (FHWA) at its Turner-Fairbank Highway Research Center (TFHRC) has been conducting an extensive research program aimed at characterizing the material properties exhibited by UHPC.[5-7] A summary of some of the results is presented in Table 2.

The table provides results for both the manufacturer recommended steam treated condition and the natural untreated condition. Steam treatment of 90°C and 95%RH for 48 hours tends to enhance the properties of the UHPC but may not be practical in all instances.

Table 2. UHPC Material Properties.

Property	Steam Treated	Untreated
Compressive Strength	28.0 ksi	18.0 ksi
Modulus of Elasticity	7700 ksi	6200 ksi
Cracking Tensile Strength (ASTM C496 setup)	1.6 ksi	1.3 ksi
Weight	155 lb/ft^3	155 lb/ft^3
Rapid Chloride Ion Penetrability (ASTM C1202)	18 Coulombs	360 Coulombs
28-day Shrinkage	850 microstrain	750 microstrain
Post-treatment Shrinkage	Negligible	N/A
Creep Coefficient	0.3	0.8

One behavior of UHPC that requires further discussion is its early age shrinkage. As would be expected from a concrete with no aggregate skeleton and high cement content, UHPC tends to exhibit large shrinkage values. Figure 1 shows the unrestrained uniaxial shrinkage behavior. During initial strength gain, shrinkage can occur at rates of up to 50 microstrain per hour. This rate soon decreases if the UHPC is left untreated; however, if steam treatment is initiated, the high rate of shrinkage can continue until more than 800 total microstrain of shrinkage has occurred. UHPC that is not steam treated will continue to shrink at an ever-decreasing rate for more than six months. On the other hand, steam treatment stabilizes the UHPC matrix with negligible shrinkage occurring after treatment.

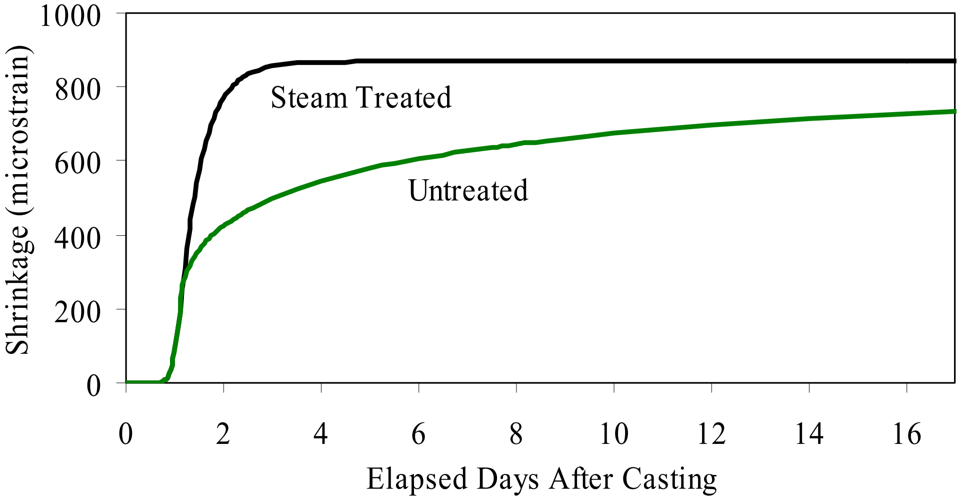

Figure 1. Early Age Shrinkage Behavior of UHPC.

OPTIMIZED GIRDER DESIGN

UHPC exhibits a set of enhanced properties that is particularly well suited to use in highway bridge structures. In terms of strength, UHPC exhibits high compressive strength, usable tensile strength, and significant post-cracking tensile toughness. These properties lend themselves to use in bridge girders, as reduced section sizes and elimination of secondary (i.e., shear, temperature, shrinkage) reinforcement may be possible. In terms of long-term stability, UHPC tends to exhibit minimal creep and shrinkage after steam treatment. These properties lend themselves to use in prestressed and/or post-tensioned concrete girders, as losses due to long-term stress-based behaviors may be reduced. Finally, in terms of durability, UHPC tends to exhibit remarkable resistance to temperature and environmentally forced degradation and to environmental contaminant ingress. These properties lend themselves to use in bridge deck structures.

Consideration of these behaviors guided the work that was undertaken to determine optimum uses of UHPC in highway bridges. A group of researchers at the Massachusetts Institute of Technology, in conjunction with the FHWA, devised a novel cross-section for prestressed concrete girders. The resulting bulbed double-tee shaped girder/deck combination is scalable depending on the span desired and is well suited to rapid construction as the deck is integral to the girder.

Figure 2 shows the optimized cross-section for a 70 foot span. This 8 foot wide girder contains twenty-two 270-ksi low-relaxation prestressing strands in its bulbs, is 33 inches deep, and weighs 23 tons. There is no mild steel reinforcement in the girder, with all secondary tensile forces being carried by the UHPC matrix and fiber reinforcement.

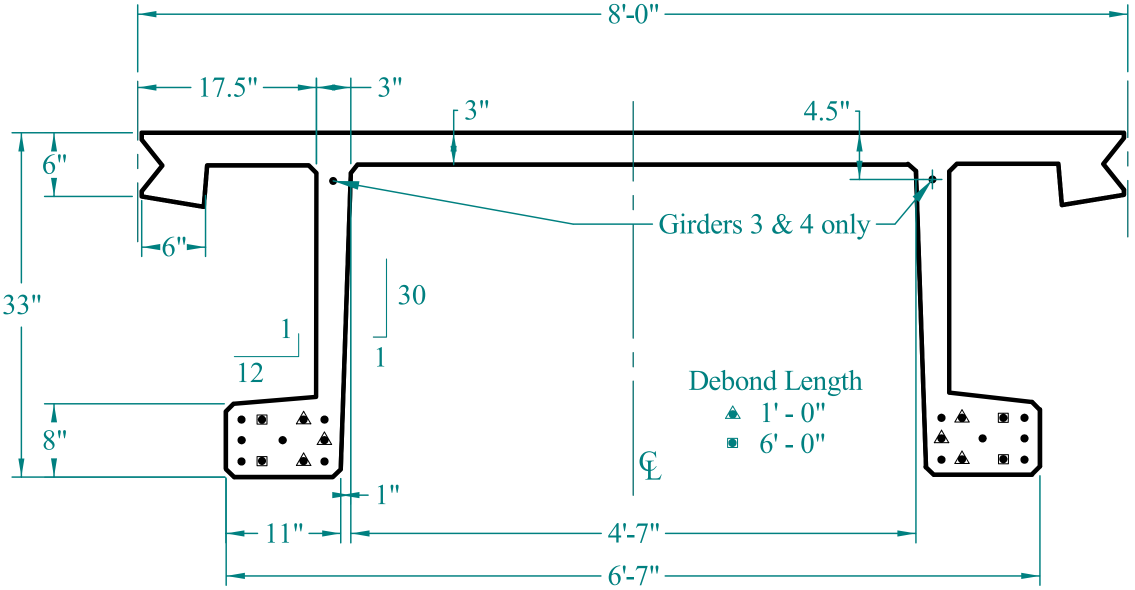

Figure 2. Optimized UHPC Girder/Deck Combination for a 70 Foot Span.

This girder is designed based on the AASHTO LRFD Bridge Design specifications.[10] The dead load includes the girder self weight and a 25 lb/ft^2 wearing surface, and the live loads are consistent with the HL-93 configuration. The girder is designed for both a service limit state where no cracking is permitted and an ultimate strength limit state.

GIRDER PRODUCTION

In order to verify the structural behavior and to determine the feasibility of construction, the FHWA has constructed four 70 foot long optimized girders. Two of these girders will be erected to form a 16 foot wide vehicle bridge at the Turner-Fairbank Highway Research Center. The other two girders will be destructively tested to aid in the understanding of how prestressed UHPC bridge girders behave.

Prestress Services of Kentucky, Inc. conducted the fabrication of these four girders in late 2003 and early 2004. The girders were fabricated one at a time in a custom-made steel form. The procedure for casting each girder included batching approximately 14.5 yd^3 of material in for separate mixes, placing the material in two ready-mix trucks, and transporting the UHPC to the form. The concrete was then deposited into the form down through each web starting at one end of the girder and working toward the other. When the webs were each one-third full, the trucks were used to fill a trough that deposited the concrete uniformly across the deck. Manual agitation and a water mist were used to ensure that there was no cold joint in the web where the two passes met. Slight, intermittent form vibration was used to aid in placement and remove some trapped air. Immediately after the deck was cast it was covered with plastic to eliminate moisture loss. Figure 3(a) shows the girder form and 3(b) shows the concrete flowing from the trough onto the deck.

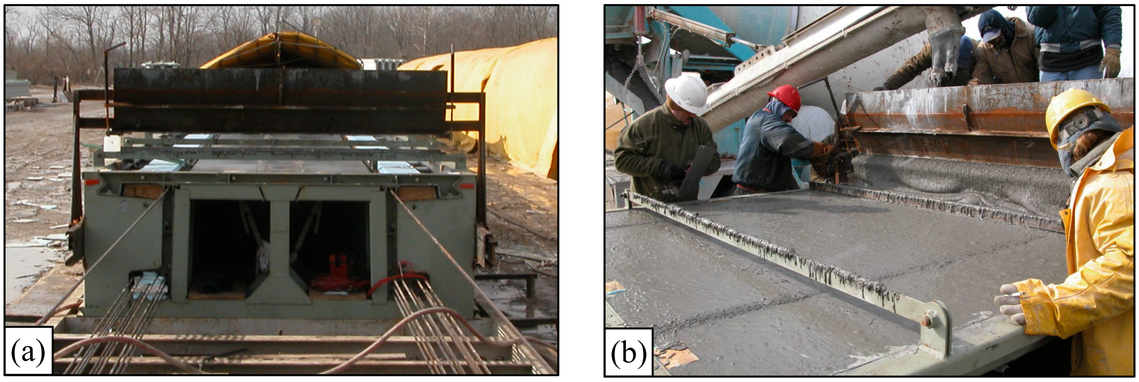

Figure 3. (a) Girder Formwork and (b) Placing the Deck.

The UHPC did not begin to set until approximately 24 hours after casting. During this time, the concrete remained semi-fluid. As the concrete began to set, internal gages began to register increases in temperature as well as shrinkage in unrestrained locations. The plastic sheeted deck also began to show increasing penetration resistance as the setting continued.

The formwork for the cross-section of this girder exhibits considerable restraint on the girder as it begins to set and shrink. The early age shrinkage behavior of UHPC is such that, if restrained beyond the initiation of setting, it will cause the UHPC matrix to crack. For this reason, the formwork for the girder included articulating inner walls that allowed the girder to shrink laterally after it had achieved sufficient strength to support itself. Each girder had to be closely monitored so that both the inner and outer formwork could be released as soon as the girder had sufficient strength to sustain itself.

The girders were designed to be prestressed when companion cylinders showed strengths of more than 10 ksi. In three of the four girders the cylinder strength was more than 13 ksi when the strands were cut. After cutting the strands, the girder was removed from the casting bed and prepared for the casting of its end diaphragms. After the girder had its diaphragms cast, it was steam treated for 48 hours and was then ready for transport to site. Figure 4(a) shows a girder just after stressing and 4(b) shows a girder after its diaphragms were cast and it had been steamed.

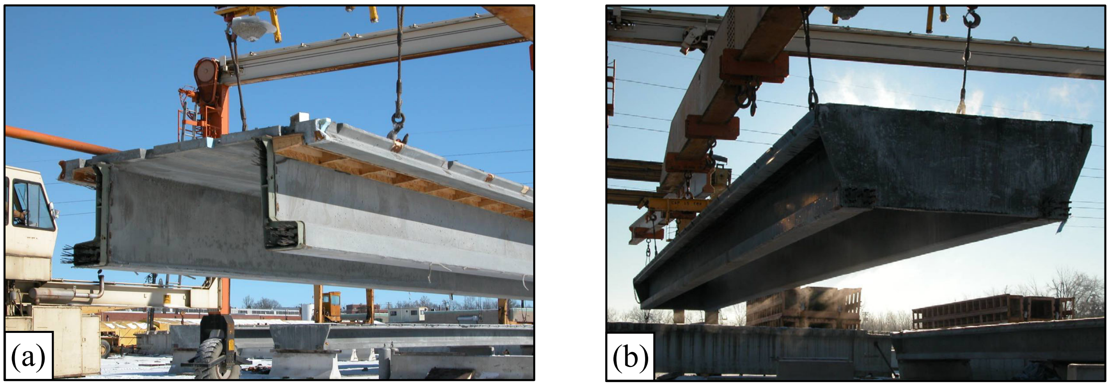

Figure 4. (a) Girder After Stressing and (b) Girder Ready for Transport.

EXPERIENCES AND FUTURE CONSIDERATIONS

The fabrication of these girders demonstrated some areas where difficulties can arise in the production of UHPC bridge girders. The areas of concern and procedures implemented to resolve potential problems are discussed below.

SHRINKAGE, RESTRAINT, AND FORMWORK RELEASE

As discussed previously, UHPC tends to exhibit significant early age shrinkage and this shrinkage can occur relatively quickly. The most significant difficulty encountered during the girder fabrication resulted from this shrinkage and the procedures that were required to address it. Different procedures were implemented depending on the location in the girder and the local flexibility of the formwork. For blockouts such as the deck overhangs and the diaphragm shear connectors, the wooden blockouts were covered in styrofoam to allow for the required movement. Accumulated shrinkage strains, such as those occurring across the deck between the webs, required larger accommodations. The rigid steel formwork that supported the fresh concrete was designed to allow for manual release of the lateral restraint that it provided between the webs of the girder. However, because this portion of the formwork also supported the gravity load of the deck, the restraint release could occur only after the deck was of sufficient strength to support its own dead weight. In effect, during a short timeframe the concrete in the deck could go from being plastic to having longitudinal restrained shrinkage cracking if the form was not released.

Under ideal conditions, the strength and shrinkage of the UHPC could be monitored to aid in determining the release time. However, in practical terms this requires three things: 1) uniform environmental conditions throughout the deck and any test pieces, 2) measurement of the unrestrained shrinkage in UHPC that has been exposed to identical conditions to the restrained UHPC in the deck, and 3) the ability to differentiate between thermally induced strains and shrinkage strains at various levels of concrete plasticity. Given the outdoor fabrication environment and the thermal behavior of various size masses of setting concrete, monitoring of temperature and shrinkage behavior was not sufficient to determine formwork release time.

A secondary method of determining deck strength was employed to verify the ability of the deck to support its own weight. Penetration resistance of the deck concrete was used as a qualitative means to determine both the degree and the uniformity of setting throughout the deck. Penetration of less than 1/8 inch with a manually forced 1/16 inch diameter flat-head penetrometer tended to indicate sufficient strength. As different parts of the deck tended to set at different rates, this method allowed the form to be released when it seemed most likely that the entire deck could support itself.

MIXING, CASTING, AND CURING

Although somewhat different than mixing normal concrete, the mixing of UHPC is not particularly difficult. The time required to mix each batch is highly dependent on the mixer. In this case each batch required approximately 45 minutes from start to finish. Given the mixer capacity, four mixes were required for each girder; thus, approximately 3 hours of mixing time went into each girder casting. The earliest mixed material required continual slow agitation in a high humidity environment so that dehydration and setting of exposed concrete did not occur.

A total of 14.5 yd^3 of UHPC was mixed for each girder casting. Each casting encompassed one girder requiring 11 yd^3 of material and various other smaller pieces (i.e., diaphragms, test slabs, cylinders, etc.) totaling approximately 1 yd^3. Each batch contained extra material to allow for lost material in the mixer and the trucks and to ensure a high flow rate of material out of the trucks into the formwork. The high flow rate was necessary, as disruptions in flow would allow dehydration and ’crusting’ of previously cast material, resulting in lenses of poor fiber content and/or orientation.

Proper casting procedures were critical to the successful casting of the girders. The two primary concerns were the proper bonding of previously cast material to newly cast material and achieving uniform fiber distribution and orientation. As discussed previously, the bonding of previously and newly cast material in the webs was accomplished through the use of a water mist to eliminate dehydration and manual agitation to mix the incoming lift with the existing one. Achieving uniform fiber distribution and orientation was accomplished through two steps. First, the UHPC was cast starting at one end of the girder with new material being continuously placed into old material. This allowed the UHPC to flow ahead of the placing location and ensured that any non-random fiber orientation would be biased toward paralleling the length of the girder. Second, the deck was cast through a trough so that there was uniform dispersal of concrete across the deck. This ensured that very little flow occurred in the deck concrete, thus increasing the likelihood of random fiber orientation.

Finally, certain UHPC curing procedures are vital to success of the final product. Most importantly, concretes containing very low water to cementitious materials ratios tend to lose surface moisture quickly when allowed to stagnate. This can lead to drying shrinkage cracks and the resulting diminution of material behaviors. Immediately after casting, any exposed concrete was sealed with plastic sheeting to eliminate dehydration. On one of the four girders this sealing was not completed in the vicinity of clamps that traversed the form and, as would be expected, drying shrinkage cracks occurred at these locations.

GIRDER STRESSING

The stressing of the girders was performed using standard techniques. However, the decision of when to stress the girders requires some discussion. Given the structural optimization inherent in the girder design, a high level of compressive strength (10 ksi) was specified to be reached prior to cutting the strands. Analysis of the girder indicates that tensile stresses in the deck caused by negative flexure could result in objectionably large cracks that extend down to near the bottom of the web. Unfortunately, the strands in one of the four girders were released when the compressive strength was 11 ksi and a large crack resulted at midspan. No midspan stressing cracks were observed in the remaining girders where strands were released after a compressive strength of 13 ksi was reached.

DIAPHRAGMS AND SECONDARY CASTS

The casting of the diaphragms onto the ends of each stressed girder demonstrated two other potential difficulties to resolve. First, forming for a ‘mortar-like’ concrete that displays many of the properties of self-consolidating concrete must be very solid and well sealed. This UHPC is capable of flowing into small openings and lacks aggregates that can aid in plugging any leaks. Even with this insight, a partial wooden formwork failure did occur on a diaphragm casting and emergency repairs were required. Also, casting of anything on this scale without external vibration can lead to poor surface finishes. The diaphragms were not externally vibrated, so they exhibit a less consistent surface finish than the girder cast surfaces.

SUMMARY

Structural optimization of prestressed concrete bridge girders for use with UHPC has been completed. The resulting cross-section for a 70 foot span is a 33 inch deep bulbed double-tee shape. Four of these girders have been fabricated using a 28 ksi compressive strength, steel-fiber reinforced UHPC. Two of these girders will be used to construct a bridge at the Turner-Fairbank Highway Research Center, while the remaining two girders will be destructively tested to determine a baseline behavior for this material/girder combination.

Although this bridge girder design is not expected to become widely used in the bridge industry, the fabrication of these girders has made it possible to identify and resolve some potential obstacles to implementation. Foremost, UHPCs tend to exhibit significant early age shrinkage, so steps must be taken to allow for this shrinkage or undesirable cracking will occur. Also, optimum behavior of fiber-reinforced concrete is dependent on proper fiber orientation, so nonstandard concrete placement methods may be necessary to ensure this condition. Finally, users must be cognizant of UHPC's requirement for enhanced quality control and monitoring during the entire casting and curing process.

ACKNOWLEDGEMENT

The research which is the subject of this paper was funded by the Federal Highway Administration with contributions from Lafarge North America, Prestress Services of Kentucky, and the Massachusetts Institute of Technology. The author gratefully acknowledges this support. The publication of this article does not necessarily indicate approval or endorsement of the findings, opinions, conclusions, or recommendations either inferred or specifically expressed herein by the Federal Highway Administration or the United States Government.

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