TECHNOTE

Construction of Field-Cast Ultra-High Performance Concrete Connections

FHWA Publication No: FHWA-HRT-12-038

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Introduction

Ultra-high performance concrete (UHPC) is an emerging construction material that has been demonstrated to advance the state of the art for construction of prefabricated bridge elements and systems (PBES). Specifically, UHPC allows for significant simplifications in the design of the component connections, while simultaneously affording enhanced durability and simplified construction practices. As of early 2012, 18 bridges in the United States and Canada have been constructed using field-cast UHPC connections, and figure 1 and figure 2 show two of those bridges. The bridge shown in figure 1 is the first in the United States to use field-cast UHPC connections. Eight simple span deck-bulb-tee girders were joined with non-contact lap splice deck-level connections. The bridge in figure 2 has precast concrete deck panels and field-cast UHPC connections. However, as with any new technology, initial deployments of field-cast UHPC technology face hurdles relating to inevitable construction process changes. This TechNote provides an introduction to many of the topics that should be considered when deploying UHPC connections.

Definition

UHPC is a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement. The mechanical properties of UHPC include compressive strength greater than 21.7 ksi (150 MPa) and sustained post-cracking

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Figure 1. Route 31 bridge in Lyons, NY.

Figure 2. Route 23 bridge in Oneonta, NY.

tensile strength greater than 0.72 ksi (5 MPa).[1] UHPC has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability compared to conventional concrete. *Ultra-High Performance Concrete* and *Material Property Characterization of Ultra-High Performance Concrete* provide further background on UHPC-class materials.[1,2] At present, UHPC is typically acquired from a supplier in three separate components, specifically a pre-bagged cementitious powder, a steel fiber reinforcement, and chemical admixtures. Water is supplied onsite. As with other pre-bagged grouts, UHPC is mixed onsite and then placed into the formwork through the use of conventional construction equipment.

Design

The design of field-cast UHPC connections is critical to the overall performance of the structural system. As opposed to conventional grouts, UHPC is frequently engaged to shorten development lengths of embedded connectors and, at times, is designed to inherently carry tensile and shear loads as a critical element within the structure. A few specific connection details, such as those discussed in *Behavior of Field-Cast Ultra-High Performance Concrete Bridge Deck Connections Under Cyclic and Static Structural Loading* and *Development of a Field-Cast Ultra-High Performance Concrete Composite Connection Detail for Precast Concrete Bridge Decks*, have been rigorously tested at service and ultimate performance limits.[3,4] The design concepts demonstrated within these tested connections are directly applicable and may be conservatively extended as new designs are considered. A variety of other connection designs have also been demonstrated to perform through field applications on bridges in the United States and Canada.

The design of UHPC connections must consider both service and ultimate limit states, as well as the practicality of construction and the long-term durability of the deployed system. Topics such as cyclic and static stress levels in the UHPC, tensile stress ranges in steel connectors, and bond strength of UHPC to conventional concrete in relation to tensile demand must all be considered. Designers and owners must recognize that a UHPC connection is necessarily connecting two or more other structural components. The UHPC connection should be designed for appropriate load-carrying capacity and long-term durability but should not be expected to address inherent shortcomings within the bodies of the connected conventional components.

[1]The tensile behavior of UHPC is generally defined as "strain-hardening," which is a broad term defining concretes wherein the sustained post-cracking strength provided by the fiber reinforcement is greater than the cementitious matrix cracking strength. However, the definitional dependence on cementitious matrix cracking strength may inappropriately include some concretes that exhibit low first-cracking strengths. Note that the post-cracking tensile strength and strain capacity of UHPC is highly dependent on the type, quantity, dispersion, and orientation of the internal fiber reinforcement.

Prefabricated Component Preparation

Prior to completing the connections between PBES components, the components must be fabricated, transported, and assembled on the bridge. These activities must be completed according to the design. In particular, the discrete connectors that emanate from the prefabricated components into the connection void space must match the design geometry. These connectors are critically important to the performance of the bridge system. UHPC affords the opportunity to reduce or eliminate field fit-up issues. As a result, designers should ensure that the constructability advantages provided by UHPC are engaged. Field assembly of components should proceed quickly, and field modification of discrete connectors should not be necessary.

The preparation of the bonding surfaces where the precast component meets the field-cast UHPC can also be of critical importance to the long-term performance of the bridge system. UHPC can bond exceptionally well to conventional concrete at these connection interfaces. However, the bond strength is highly dependent on the surface of the precast concrete. As with other cementitious grouts, UHPC is not likely to form a strong bond with smooth, dry, precast concrete. On the other end of the spectrum, UHPC cast against a concrete element with an exposed aggregate surface finish has been demonstrated to provide enhanced bond. Prewetting of a precast concrete interface to a saturated surface dry condition immediately before UHPC casting is generally beneficial because it eliminates the dehydrating effect that can occur when dry concrete extracts water from the mating UHPC. Field-applied epoxy bonding agents and concrete form liners are other options for enhancing the bond.

Formwork

The formwork required to contain UHPC placed into a connection requires somewhat tighter control than the formwork commonly deployed in field-cast concrete applications. Rheologically, UHPC is a self-consolidating concrete that contains little or no coarse aggregate. As such, UHPC exhibits higher formwork pressure than conventional concrete and can easily leak between formwork that is not appropriately sealed. As opposed to conventional concrete, the lack of blocking elements (i.e., coarse aggregate) within UHPC results in formwork leaks that continue to flow and expand unless immediate firm action is taken to stop a leak.

Success or failure of formwork on past projects has been directly attributed to contractor attentiveness to the need to ensure that formwork is sealed and capable of resisting the hyrdostatic pressure that UHPC imparts. Contractors who expect UHPC to behave like conventional concrete have been proven wrong, while contractors who recognize the differences and prepare appropriately have achieved success. Some contractors have gone so far as to temporarily fill connection forms with water to ensure leak tightness and pressure resistance. Although not necessary, this activity can prove beneficial.

Forms for field-cast UHPC should be designed to allow for either slight overfilling or slight overpressure as the pour is completed. Small amounts of air trapped both in UHPC and in the connection spaces can result in UHPC initially appearing to fill the void space but later exhibiting slight subsidence as the air escapes. For deck-level connections, wood or foam strips are frequently installed on either side of the connection to allow it to be overfilled. Additionally, the formwork is frequently designed to allow for UHPC to be enclosed (i.e., top-formed) immediately after the placement in one area is completed. In nearly all cases, formwork is designed to allow for a UHPC "chimney" to be cast, thus providing extra UHPC which can fill subsided areas. This "chimney" is akin to the sprue in the metal and plastic component casting industries. It allows for a slight overpressure on the field-cast UHPC which assists in ensuring that the connection space is fully filled.

It can be advantageous to include portions of formwork on prefabricated components, thus lessening the demand for field-installed formwork. For instance, adding formwork to prefabricated components, such as concrete lips at deck panel connections, can simplify the field construction activities. However, it should be recognized that the field benefits afforded through these sorts of modifications can increase the cost and complexity of the prefabrication activities.

Mixing and Placing

As with any pre-bagged cementitious composite, UHPC must be mixed according to the supplier's specifications. These specifications frequently provide information on the constituent volumes to be mixed and the order of constituent addition to a particular mixer. UHPC is sensitive to mixing deviations, so mix proportions and timings must be followed. The addition of water or chemical admixtures beyond those specified can cause detrimental impacts on the early and long-term performance of the field-cast UHPC.

The weather conditions surrounding the UHPC prior to and during mixing can impact the fresh properties of the concrete. The temperature of the UHPC will increase during mixing, and some mix water will be lost due to evaporation. Mixing UHPC under cool temperatures and away from direct exposure to sun and wind is advantageous. Maintaining a reduced temperature on the pre-bagged UHPC powders and the mix water is advantageous. The fluidity of UHPC can become reduced, and the likelihood of surface dehydration can increase if the temperature of UHPC at the conclusion of mixing exceeds 80 °F (26.7 °C). Cubed ice has been demonstrated to be a viable replacement for some or all of the mix water when mixing in warm conditions.

UHPC can be mixed in most concrete or grout mixers. UHPC mixing requires a significant energy input in order to disperse the liquids uniformly within the powder matrix. Higher energy mixers will complete the mixing process more quickly. Both tow-behind pan mixers and conventional concrete ready-mix trucks have been used to mix UHPC. As a rule-of-thumb, the volume of UHPC that can be mixed in one of these mixers is approximately half of the volume of conventional concrete that could be mixed in the same mixer. Figure 3 shows a portable concrete pan mixer preparing UHPC for placement during the construction of the field-cast connections on the Keg Creek Bridge in Council Bluffs, IA.

The choice of mixer should be determined based on the rate of UHPC delivery required at the construction site. Frequently, a field-cast connection between bridge components may require more UHPC than can be quickly delivered. As such, the connection needs to be divided into smaller sections so that the placement rate allows the UHPC to quickly fill the divided connection space. This requirement is based on the fact that, like conventional concrete, UHPC is susceptible to surface dehydration, which can lead to the appearance

Figure 3. Portable concrete pan mixer preparing UHPC for placement during the construction of the field-cast connections.

of a false set in a thin layer on the concrete surface. Subdivision of connection spaces is most critical for deck-level connections between precast concrete elements. These connections are fully exposed to the weather during casting, possibly leading the exposed surface of the UHPC to desiccate and crack prior to the form being filled. Methods of estimating conventional concrete surface dehydration rates are available and should be engaged to assist in coordinating construction activities.[5]

Traditionally, the placement of UHPC into field-cast connections has been completed through the use of motorized or non-motorized wheelbarrows, with connection spaces being filled consecutively. Figure 4 shows UHPC placement on a bridge in Lyons, NY. It is also possible to pump, augur, or chute UHPC; however, these methods may result in temporarily stagnant UHPC exhibiting poor rheological performance when placed in the connection.

UHPC should always be placed into connection spaces so that successive placements are poured into previously placed UHPC. UHPC is a steel-fiber reinforced concrete and, depending on the structural design of the connection, may rely on the tensile capacity afforded by those fibers. When two "heads" of adjacent UHPC pours meet one another, an interface is formed wherein there is limited interface crossing by the fiber reinforcement. This situation can be avoided by pouring fresh UHPC into UHPC which was recently cast and remains fluid.

UHPC is self-leveling, and this fact must be considered when designing formwork and placing UHPC. UHPC is commonly placed beginning at the lowest point within any formwork pour area and moving toward the highest point. Filled areas of lower elevation need to be top-formed (i.e., closed) in order to stop UHPC from overflowing the connection. For deck-level connections, this top-forming can be accomplished through the use of plywood strips, which are placed over the field-cast UHPC and are fastened in place. The placement concludes at the "chimney."

Figure 4. Longitudinal connections cast between deck-bulb-tee girders on the Route 31 bridge in Lyons, NY.

Photo from New York State Department of Transportation.

Traditional concrete finishing techniques are not normally employed on field-cast UHPC. The high supplementary cementitious materials content and the low water content restrict the ability to draw water-rich paste to the surface of the concrete. As such, alternate techniques must be employed to ensure an appropriate concrete surface is delivered. Most commonly, UHPC is either cast in a closed form, or the form is closed immediately after casting. The closed form should be designed to allow full filling of the connection space without the trapping of air. UHPC should be in contact with the top formwork, minimizing the surface dehydration that can occur on exposed surfaces of fresh-cast UHPC. On horizontal surfaces that will eventually be exposed to the public, the connection is frequently overfilled. This allows the UHPC surface to be ground to match the adjacent pre-fabricated surfaces.

Initial and Final Curing

The formulations of UHPC-class materials tend to result in concretes that exhibit long dwell times prior to the initiation of setting behaviors. However, once setting begins, strength gain rapidly occurs. The initial setting behaviors are dependent on the temperature of the UHPC. Although cooler temperatures are beneficial for mixing and placing UHPC, warmer temperatures are beneficial for the rapid setting of the concrete. Supplemental heat can be supplied to the UHPC and the surrounding prefabricated elements in order to accelerate the initial setting. This heat can be supplied externally (e.g., ground heating mats) or internally (e.g., resistance heating wires) but should not be applied via forced air heat against exposed UHPC surfaces. The application of supplement heat can be especially important for accelerated bridge construction projects and for projects that are being completed in cold weather. In order to reduce the risk of surface dehydration, the UHPC should remain sealed from exposure to the external environment prior the completion of initial curing. Also, UHPC should not freeze during initial curing.

After the attainment of sufficient strength, the formwork may be stripped, and UHPC may be exposed to the environment. The cementitious reactions inherent in the UHPC formulation will continue to occur as the full complement of mechanical and durability properties are achieved. UHPC may be, but does not need to be, kept moist during the final curing phase. The structure may be subjected to construction and/or traffic live loads during the later phases of the UHPC strength gain; however, care must be taken not to overstress the connections prior to the attainment of the design strength.

Surface Profiling

Horizontal field-cast UHPC surfaces, such as the exposed surface on the top of a deck-level connection, must be dressed to provide appropriate rideability. Frequently, both the UHPC and the top face of the precast concrete deck component are designed with a sacrificial surface that can be removed after the connections are cast and the UHPC has gained a portion of its design strength. Grinding the entire surface of the deck eases the construction requirements pertaining to the profile of the bridge deck and simplifies the creation of a consistent driving surface.

Both grinding and grooving operations of field-cast UHPC connections (and surrounding precast component decks) have been conducted on the previously completed projects. Some contractors have reported that grinding/grooving UHPC is easier if completed prior it reaching its full design strength. The ease with which these operations can be completed depends on the UHPC strength, the UHPC formulation, and the type of grinding/grooving equipment deployed. UHPC formulations designed to exhibit exceptional abrasion resistance will be more difficult to dress than traditional UHPC formulations.

Material Testing

In general, well-established testing procedures for conventional concrete are applicable to UHPC. However, in some instances, procedures may need to be modified in order to appropriately capture the true behaviors of UHPC. Compression testing and flow testing are prime examples.

Flow Testing

The rheological properties of UHPC are traditionally captured through the use of the ASTM C1437 test (see figure 5).[6] This test, which is basically a miniature version of the traditional slump test, measures the flow of hydraulic cement mortars. Both an initial flow reading and a dynamic flow reading are recorded. Frequently, this test is completed immediately after mixing in order to assess consistency between mixes and appropriateness for casting.

Compression Testing

As with conventional concrete, compressive strength is an oft used indicator of the mechanical properties of UHPC. Research has demonstrated that standard concrete compression testing methods (i.e., ASTM C39 and ASTM C109) are applicable to UHPC.[7,8] However, these test methods may benefit from slight modification to facilitate efficient use. Most notably, a loading rate of 150 psi/s (1 MPa/s) has been demonstrated to be

Figure 5. ASTM C1437 flow test on UHPC.[6]

acceptable, allowing individual tests to be completed in a reasonable timeframe.[9]

It has also been demonstrated that at the high-strength levels achieved with UHPC, both reduced-size cylinders and reduced-size cube compressive test specimens are an appropriate substitute for full-size cylinders. Companion cylinder and cube strength results tend to be within 5 percent of one another, allowing for direct substitution of results.[10]

If cylinder tests are used for specimens at strength levels above those appropriate for capping methods, both cylinder ends must be ground planar to within the ASTM C39 specification of 0.5 degrees.[7] It is also important to recognize that the high compressive strengths of UHPC may necessitate the use of higher capacity compression testing platens and machines.

Both 3-inch- (76-mm)- and 4-inch- (102-mm)-diameter cylinders are frequently used to assess the compression strength of UHPC on highway projects completed in the United States and Canada. If used for assessment of the curing behaviors of a field-cast connection, these cylinders should be match cured with the connection.

Summary

UHPC has captured the interest of bridge owners across the United States as they look for innovative solutions to facilitate rapid and robust construction of highway bridges. As with any new technology, the first round of implementations requires extra oversight, as front-line workers adjust common practices to align with new requirements. This TechNote is intended to provide insight into practical details associated with the use of field-cast UHPC for connections between prefabricated bridge elements. Recognition of the topics discussed herein should increase the likelihood of successful deployments of UHPC technology by owners across the United States.

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Key Words—Ultra-high performance concrete, UHPC, Fiber-reinforced concrete, Bridge, Accelerated construction, Durable infrastructure system, Prefabricated bridge elements and systems, Field-cast connections, Test methods.

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APRIL 2012

FHWA-HRT-12-038
HRDI-40/04-12(300)E