TECHNOTE

Design and Construction of Field-Cast UHPC Connections

FHWA Publication No: FHWA-HRT-19-011

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This document is an update to *Design and Construction of Field-Cast UHPC Connections* (FHWA-HRT-14-084).

Introduction

Advancements in the science of concrete materials have led to the development of a new class of cementitious composites called ultra-high performance concrete (UHPC). UHPC exhibits mechanical and durability properties that make it ideal for use in new solutions to pressing concerns about highway-infrastructure deterioration, repair, and replacement.[1,2] The use of field-cast UHPC details that connect prefabricated structural elements in bridge construction has captured the attention of bridge owners, specifiers, and contractors across the country. These connections can be simpler to construct and can provide more robust long-term performance than connections constructed through conventional methods.[3] This document provides guidance on the design and deployment of field-cast UHPC connections.

UHPC

UHPC is a fiber-reinforced, portland cement–based product with advantageous fresh and hardened properties. Through advancements in superplasticizers, dry-constituent gradation, fiber reinforcements, and supplemental cementitious materials, UHPC outperforms conventional concrete. Developed in the late 20th century, this class of concrete has emerged as a capable replacement for conventional structural materials in a variety of applications.

The Federal Highway Administration (FHWA) defines UHPC as follows:

> 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. In general, the mechanical properties of UHPC include compressive strength greater than 21.7 ksi (150 MPa) and sustained post-cracking 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.[2]

An alternative name for UHPC is ultra-high performance fiber-reinforced concrete (UHPFRC).

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For the purposes of this document, UHPFRC is synonymous with UHPC since fiber reinforcement is a key component of the FHWA definition of UHPC.

In-Service Performance

Since 2006, nearly 300 bridges have been constructed with field-cast UHPC connections and precast bridge elements and systems in North America.[4] A 2012 cursory field examination of the overall performance (e.g., connection leaking or reflective cracking) of over 40 of these bridges constructed in Ontario, Canada; Iowa; and New York indicated that these UHPC connections were performing well.[5]

UHPC Material Properties

Given that UHPC is a class of materials and that different mix designs will lead to different performance attributes, FHWA recently completed a study investigating the material properties of five different products that are being marketed as UHPCs.[6] One goal of this study was to provide a sense of material properties that can be expected when specifying UHPC on a project. Table 1 presents the observed range of performance for a suite of properties, including fresh, mechanical, durability, and dimensional stability.[6,7] In terms of the design and construction guidance provided in this document, some properties hold greater relevance than others, depending on the specific project requirements. Sustained postcracking tensile capacity is central to the structural performance of UHPC connections. Specific flow properties may be necessary, depending on the connection geometry and the casting method. Interface bond and durability properties are often important in terms of the long-term performance of the deployed structural system.

Constituents

Like conventional concrete, UHPC is composed of a variety of constituents that are combined in a mixer to create a semifluid product that can be placed into formwork and, with time, will develop a particular set of properties. The common constituents of UHPC include dry components, fiber reinforcement, chemical admixtures, and water. Because UHPC, like conventional concrete, is defined by the properties of the composite material, multiple formulations may produce similar characteristics.[21] Examples of various UHPC compositions can be found in chapter 2 of the FHWA publication *Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community*.[1] The following information on constituents speaks to common UHPC formulations.

As with all concretes, UHPC formulations must be developed with a focus on a range of performance considerations. Compatibility of constituent components is a key consideration. Exact compositions, particle geometry, and reactivity may vary. Any modifications of existing mix designs or products through the addition or subtraction of constituents should be completed with care.

Dry Components

Dry components comprise the majority of the UHPC constituents. These components include portland cement, silica fume, and fine aggregates. UHPC formulations may also include small coarse aggregates and supplementary cementitious materials.

A variety of portland cements are produced in the United States, and each cement performs in a specific way. The portland cement used in UHPC may be produced to meet the standards of ASTM C150 and American Petroleum Institute Specification 10A.[22,23] Class H oil-well cements are frequently included in UHPC mixes.

Silica fume is a key component in UHPC because of its reactivity and small particle size. UHPC commonly includes a high proportion (10 percent or more relative to the weight of cement) of silica fume.

[1]The tensile behavior of UHPC may generally be defined as "strain-hardening," a broad term defining concretes in which the sustained postcracking strength provided by the fiber reinforcement is greater than the cementitious matrix cracking strength. 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.

Table 1. Expected range of material properties of field-cast UHPC.

Property	Test Method and Details	Expected Range
Density	ASTM C642[8]	144–157 lb/ft^3 (2,300–2,510 kg/m^3)
7-day compressive strength	ASTM C1856[9] ASTM C39[10]	14.5–19.5 ksi (100–135 MPa)
14-day compressive strength	ASTM C1856[9] ASTM C39[10]	18–22 ksi (125–152 MPa)
Modulus of elasticity	ASTM C1856[9] ASTM C469[11]	4,250–8,000 ksi (29–55 GPa)
Poisson's ratio	ASTM C1856[9] ASTM C469[11]	0.12–0.2
Direct tension cracking strength	FHWA-developed direct tension test[12]	0.8–1.2 ksi* (5.5–8.3 MPa)
Direct tension sustained postcracking tensile strength	FHWA-developed direct tension test[12]	0.8–1.2 ksi* (5.5–8.3 MPa)
Direct tension strain capacity prior to crack localization	FHWA-developed direct tension test[12]	0.003–0.004
Direct tension bond strength (interface failure)	ASTM C1583, bonded to an exposed aggregate surface[13]	0.35–0.6 ksi (2.4–4.1 MPa)
Long-term creep coefficient	ASTM C1856[9] ASTM C512[14] (Compressive strength > 17 ksi (117 MPa); Sustained stress = 37–53% of the compressive strength at initial loading)	0.7–1.2
Long-term drying shrinkage	ASTM C1856[9] ASTM C157[15]	300–1,200 microstrain
Long-term autogenous shrinkage	ASTM C1856[9] ASTM C157[15]	200–900 microstrain
Chloride ion penetrability	ASTM C1856[9] ASTM C1202[16] 56 days after placement	50–500 coulombs
Freeze–thaw resistance	ASTM C1856[9] ASTM C666[17] After 600 cycles	RDM > 98%
Initial setting time	ASTM C403[18]	4–10 hour
Final setting time	ASTM C403[18]	7–24 hour
Static flow	ASTM C1856[9] ASTM C1437[19]	4–10 inches (100–250 mm)
Dynamic flow	ASTM C1437[19]	7.5–10 inches (190–250 mm)
Alkali-silica reaction	ASTM C1260[20] Tested for 28 d	Innocuous

*The expected range of values for direct tension sustained postcracking tensile strength is the same as the expected range of values for direct tension cracking strength. This equivalence is because, for a strain-hardening material like UHPC, the minimum value of direct tension sustained postcracking tensile strength is the direct tension cracking strength.
RDM = relative dynamic modulus of elasticity.

The fine aggregates are proportioned and sized to allow a gradation of dry constituents that facilitates flow in the fresh UHPC. A variety of fine aggregates—including quartz, limestone, and basalt—can be appropriate for use in UHPC.

Coarse aggregates are sometimes included in UHPC formulations. These aggregates tend to be relatively small (0.25 inch (6 mm) or less) and included at low proportions compared to conventional concrete.

Other supplementary cementitious materials—including fly ash, metakaolin, ground granulated blast furnace slag, and limestone powder—have been considered for inclusion in UHPC formulations.

The dry components of the cementitious composite are available from a variety of sources. Exact chemical compositions, particle geometry, and reactivity may vary, so developers of UHPC mix designs are advised to consider compatibility issues, fresh-concrete properties, and hardened-concrete properties.[12]

Chemical Admixtures

Chemical admixtures used in UHPC are readily available in the concrete industry. These admixtures commonly include accelerators, polycarboxylate-based superplasticizers, and phosphonate-based superplasticizers. Other admixtures could also be used in support of a specific need on a particular project. These chemicals are proportioned according to the project requirements to provide self-consolidating properties of UHPC in an unhardened state and to encourage specific postplacement material behaviors.

Water

The cementitious reaction that is inherent to the use of portland cement–based composites requires an adequate supply of potable water. Common requirements for water quality and water control relevant to conventional concrete are also applicable to UHPC.

The temperature of the water during its addition to the mixer plays a key role in achieving appropriate fresh properties. Chilled water and ice are commonly used to reduce the temperature of UHPC during mixing and placement. This temperature reduction facilitates an increase in the fluidity of the mix and a reduction in the rate of free-water evaporation from the mixed UHPC. In addition, cubed ice increases the efficiency of the mixing process by providing both better mixing action in the powder-rich UHPC formulations and a sustained supply of water throughout the mixing process as the ice melts. All ice should be melted, and the resulting water should be well mixed into the UHPC prior to mixer discharge.

Steel Fiber Reinforcement

Steel fiber reinforcement is a critical component of UHPC when used in structural elements or field-cast structural connections. The exceptional mechanical properties of UHPC can be largely attributed to the fiber reinforcement. These properties cannot be achieved without inclusion of specific fibers that afford appropriate fiber efficiency to the composite matrix. Fiber efficiency is influenced by fiber type, geometry, volume fraction, dispersion, and orientation. Mix design and casting technique contribute to the final mechanical performance.

A UHPC mix design or product must include specific information regarding fiber type, geometry, and volume fraction. The cementitious composite formulation is commonly designed in conjunction with the fiber-reinforcement constituent to deliver the requisite fresh and hardened properties.

The field-cast UHPC connections described in this document require steel fiber reinforcement included at high volumes compared to conventional fiber-reinforced concretes. The fiber proportion by volume is normally 2 percent of the volume of the overall UHPC composite. Steel fiber reinforcement provides superior crack-bridging capabilities compared to lower-stiffness fiber reinforcements. Steel fibers are typically made of high-strength steel to ensure that fiber tensile failure does not occur. Fibers may be straight or deformed.

The most common steel fiber (figure 1) deployed in UHPC applications is a 0.008-inch (0.2-mm)-diameter by 0.5-inch (13-mm)-long straight fiber with a specified minimum tensile strength of 290 ksi (2,000 MPa). Domestic production of this type of fiber has been available since 2013, and commercial suppliers of UHPC for projects in the United States typically provide domestically produced fibers. As a result, adherence to the Buy America provisions of Federal law is generally not an issue.[24]

Figure 1. Photo. Commonly used steel fiber reinforcement.[25]

Source: FHWA.

Availability of UHPC

The sophistication of UHPC cementitious composites has facilitated a worldwide network for the production and distribution of preblended UHPCs. Typically, multinational construction-material suppliers produce a set of products in this class. The dry constituents, chemical admixtures, and steel fiber reinforcements are delivered to the project site, where they are mixed with water to produce fresh UHPC. This production and distribution model is similar to the one commonly used for many of the proprietary grouts and patching materials frequently deployed in the construction of public infrastructure.

FHWA released a memorandum on the topic of UHPC on February 12, 2014.[26] This memorandum addressed domestic supply of steel fiber reinforcement as well as proprietary product considerations. It also included two attachments. Attachment A was the New York State Department of Transportation (NYSDOT) UHPC specification dated April 19, 2013. Attachment B, titled *NYSDOT UHPC Implementation Notes*, spoke to specific applications and considerations from the perspective of the owner. Individuals and owners considering the use of UHPC for field-cast connections are encouraged to consult this memorandum.[26] NYSDOT continually updates its UHPC specification based on the latest research and experience; thus, the most recent version should be consulted in lieu of the version contained in the FHWA memorandum. More recent versions of the NYSDOT specification can be accessed on NYSDOT's website.[27]

Common UHPC Connections

Prefabricated bridge elements (PBEs) can be used to accelerate onsite construction and increase the quality and durability of bridges. To benefit from PBEs, these elements need durable connections that are easy to construct. UHPC's material and durability properties create opportunities to modify and improve PBE connection details. In addition to the high-compressive and postcracking tensile strengths, the dense, discontinuous pore structure and steel fiber reinforcement of UHPC provide further material-property benefits. Improvements include better internal distribution of stresses, better confinement of embedded rebar, and reduced rebar development and splice lengths.

UHPC mix designs currently being used require at least 12 hours to gain sufficient strength before being subjected to construction or traffic loads. When there is less than 12 hours available in the construction schedule for UHPC to cure, an alternate connection material should be considered.

Adjacent Precast Deck Panels—Lap Splices

The simplest and most common connection detail involves the lap splicing of mild steel reinforcing bars. For rebar in tension, the American Association of State Highway and Transportation Officials' (AASHTO's) current edition of *AASHTO LRFD [Load and Resistance Factor Design] Bridge Design Specifications* requires a minimum development length of at least 24 times the nominal bar diameter (d_b).[28] Frequently, the length can be $36d_b$ or larger. Long lap lengths may lead to undesirably large connections; alternatives include using hoops, hooks, headed rebar, or mechanical couplers.

For rebar embedded in UHPC, the tension development length is a fraction of the length needed in conventional concrete. As a result, structural elements can be connected by shorter, straight lengths of rebar in a manner significantly less complicated than connections that use conventional concrete or grout.[29] Reinforcement costs, difficulties in fabrication, and challenges with field assembly are all factors that can be positively addressed by specifying field-cast, lap-splice connections with UHPC.

Connections between precast bridge deck panels are one example of a field-cast connection that takes advantage of UHPC. Rebar from one panel overlaps with the rebar from an adjacent panel, and the void between them is filled with UHPC. The connection transfers moment, shear, and tensile forces across the joint using short, straight rebar spaced at intervals typical to conventional deck design. The width of the connection is based on the rebar development and lap-splice lengths plus construction tolerance. Many constructed bridge deck panel connections have widths that vary between 6 and 8 inches (152 and 203 mm). The connections are detailed with a shear key configuration to facilitate load transfer across the joint.

A typical precast deck connection detail is shown in figure 2. This illustration shows the transverse connection detail, in which the top and bottom longitudinal reinforcing bars are lap spliced in the connection, between adjacent panels. Figure 22 shows a photograph of the precast-deck connection detail, which has a width of 6.5 inches (165 mm), used for I-81.

Deck Panel to Girder—Composite Action

The conventional detail used to connect prefabricated deck panels to girders requires shear studs or rebar extending from the girder into block-out pockets in the deck that are filled with grout to create a composite deck/beam structure. The placement of the block-out pockets may cause clearance challenges with rebar and other associated hardware (post-tensioning, lifting lugs, leveling bolts, drainage assemblies, etc.) during panel fabrication. For certain bridge configurations, the large number of shear connectors required may result in congested, or even unworkable, block-out pocket configurations. Deck overlays, which require an additional construction activity, are typically installed over prefabricated deck panels to address concerns about water ingress through the cold joint between the precast panel and shear stud pocket. Overlays are also used to address the long-term performance and wearability concerns regarding conventional grout surfaces in direct contact with repeated wheel loadings.

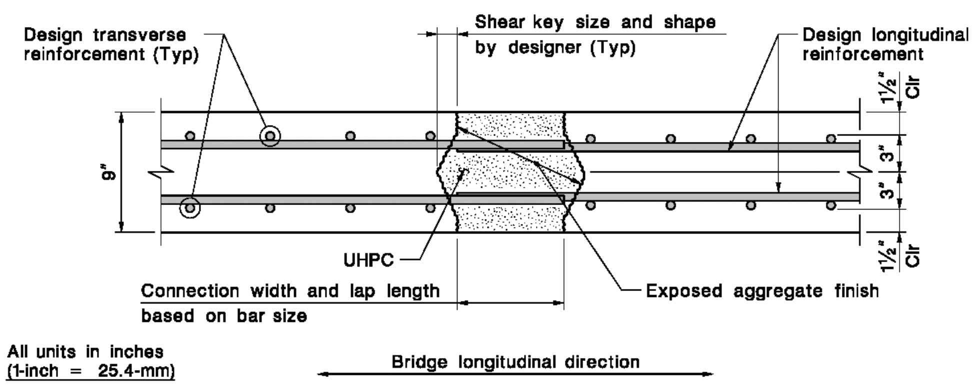
Details that use UHPC can improve the conventional block-out pocket detail. Congestion issues associated with the rebar and hardware used in the prefabricated panel can be addressed through a reconfiguration of the conventional shear-pocket concept. Elimination of a deck overlay can also become a viable option because of UHPC's ability to bond to adjoining precast surfaces and the discontinuous pore structure that nearly eliminates liquid ingress. The self-consolidating properties allow UHPC to flow into tight spaces, thus offering the opportunity for a continuous, hidden connection detail that eliminates the need for the conventional shear pocket detail altogether. UHPC also has the ability to improve internal stress distribution, thus enhancing the composite action between the prefabricated panel and supporting beam.

This connection concept has been deployed in U.S. bridges on a variety of roadways, including county routes and interstate highways. In each of these slab-on-stringer bridges, the height of the shear connectors remains below the bottom mat of deck panel rebar to simplify the deck panel installation. Inherent in this concept is the reliance on UHPC to carry the tensile, compressive, and shear stresses between the deck and girder connectors.

One example of this connection detail is shown in figure 3 and figure 23. This detail was deployed on a series of interstate highway bridges near Syracuse, NY. The detail combines the panel-to-panel connection detail with the deck-to-girder connection detail into a single casting of field-cast UHPC connection that runs along the girder line.

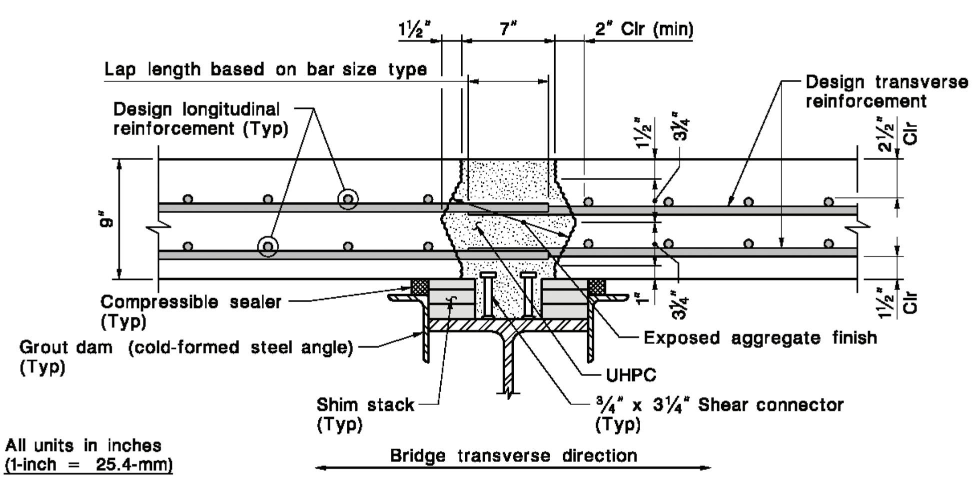
Another example of this connection detail is shown in figure 4, figure 24, and figure 25. This detail is the hidden-pocket version in which a continuous pocket is created above the girder line and then filled with field-cast UHPC. Composite action is generated through transfer

Figure 2. Illustration. Typical UHPC connection between precast deck panels.



Source: FHWA.

Figure 3. Illustration. Combined UHPC deck-level and composite connections as deployed by NYSDOT on I-81 near Syracuse, NY.

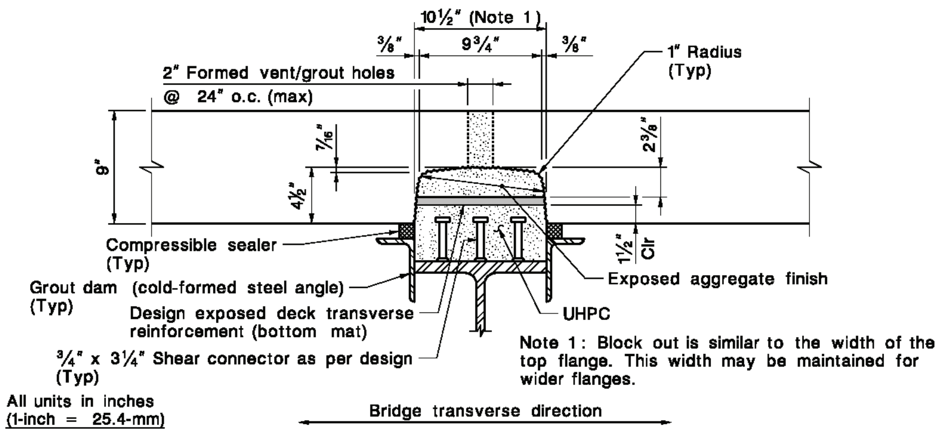


Source: FHWA.

of forces between the girder and the deck through UHPC. This detail was deployed on the CR47 bridge over Trout Brook, near Stockholm, NY.

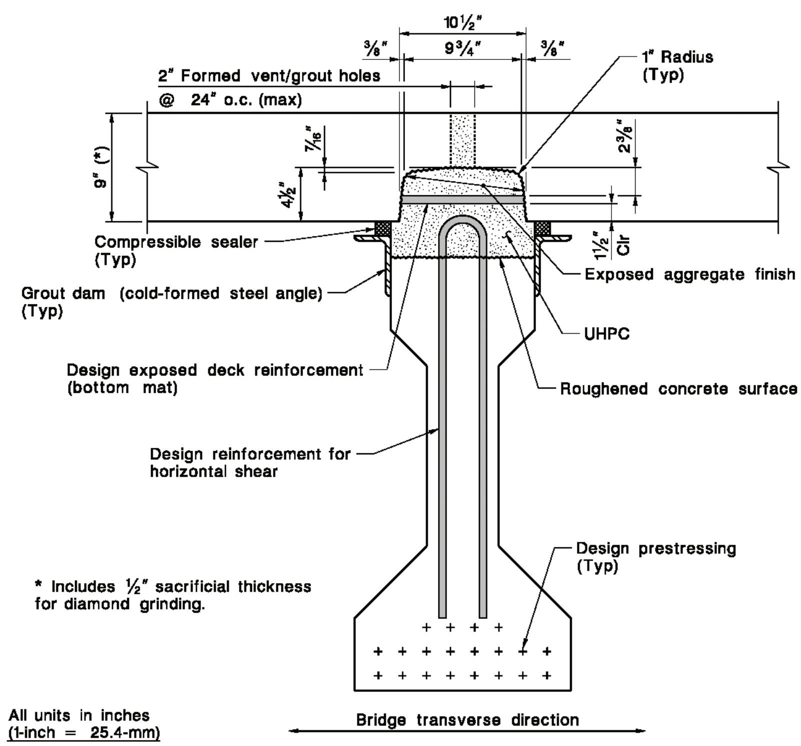
Figure 5 is a final example of this detail with a concrete girder that demonstrates a hidden-pocket concept similar to that shown in figure 4. The configurations in figure 4 and figure 5 have been laboratory tested and demonstrate adequate structural performance under fatigue, service, and strength loadings.[30] The detail in figure 5, however, has yet to be deployed in the U.S. bridge inventory.

Figure 4. Illustration. UHPC composite connection between deck panel and steel girder.



Source: FHWA.

Figure 5. Illustration. UHPC composite connection between deck panel and concrete girder.



Source: FHWA.

The hidden-pocket concept can be used with self-consolidating conventional concrete, grout, or UHPC. With UHPC, however, the shear connectors extending from the girders can be detailed to terminate below the bottom mat of rebar in the deck since UHPC is able to transfer the shear forces between the deck and the girder.

Adjacent Box Beams and Other Longitudinal Elements

UHPC connection details have also been developed for use in adjacent box-beam bridges. Conventional connection details include grouted shear keys and intermittent transverse post-tensioning. These traditional details have often exhibited poor performance, resulting in differential deflection between beams, overlay cracking, water ingress, and eventually, connection failure.

Similar to deck-level connections between precast concrete bridge deck panels, field-cast UHPC connections that bond to the precast interfaces and use a lap-splice reinforcement detail can create an improved structural connection that is capable of transferring shear, moment, and axial tensile and compressive forces across the connection. The UHPC detail eliminates the need for transverse post-tensioning or a structural concrete overlay. In effect, this detail creates a continuously reinforced concrete slab at the top flange level of the boxes. FHWA has performed significant research on the performance of adjacent box-beam connections.[31,32]

The Sollars Road Bridge over Lees Creek in Fayette County, OH, is the first box-beam bridge in the United States to use this UHPC detail. This 61-ft (18.6-m)-span bridge contains seven adjacent box beams. The prestressed boxes are 4 ft (1.2 m) wide and 21 inches (533 mm) deep with 7-inch (178-mm)-deep shear keys on either side. Because no transverse post-tensioning is required, these boxes did not require intermediate diaphragms. Figure 6 shows the connection detail in which adjacent box beams would be butted together and the reinforcing bars would lap within the connection. A photograph of this connection is included in figure 33.

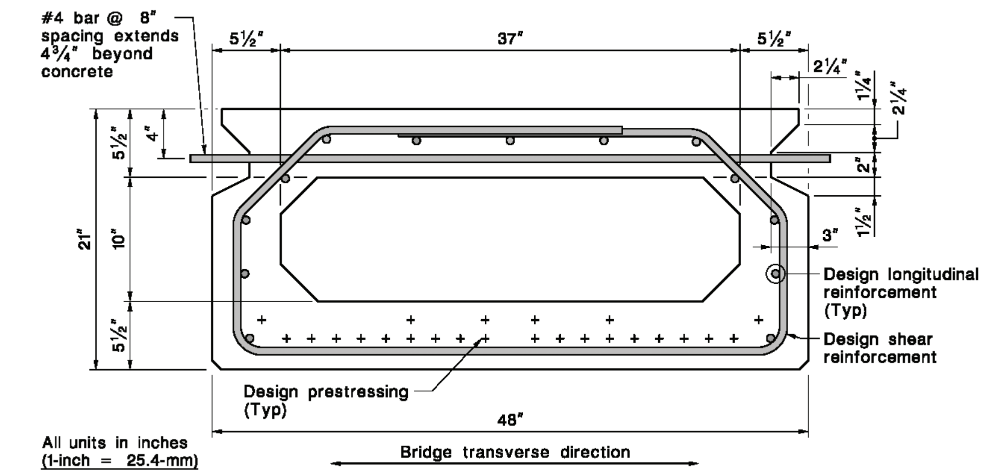
This detail is also applicable to voided (hollow-core) slab beams as well as other types of decked girder bridge systems. The detail could easily be applied to the flange tips of deck-bulb-tee girders; Northeast Extreme Tee, or NEXT, beams; and pretopped steel modular units. In addition to reducing or eliminating the need for transverse post-tensioning and a structural concrete overlay, UHPC connections eliminate the need for welded shear tabs, which are sometimes used to hold adjacent decked girders together. This detail also lends itself to top–down construction in which access to the underside of the superstructure is limited or unavailable.

Link Slabs

Another potential application of field-cast UHPC connections is with link slabs above the interior supports of multiple, simple-span bridge structures. The intent of the connection is to eliminate the need for strip seals or other traditional joint systems by creating a durable structural element spanning between the adjacent bridge decks.

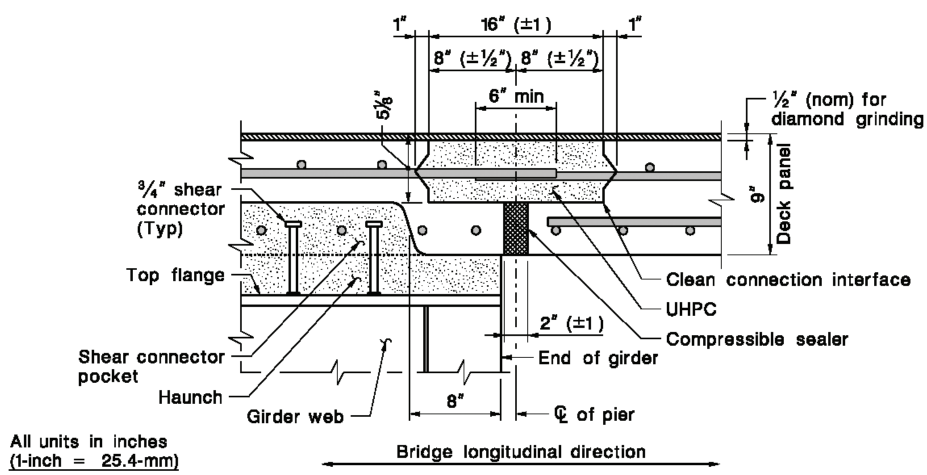
NYSDOT used this connection detail during the deck reconstruction of the SR962G bridge over U.S. Route 17 in Owego, NY. The link-slab detail is illustrated in figure 7 as a split-section view with the left side at the girder line and the right side midway between girder lines. This project used precast concrete deck panels and field-cast UHPC lap-splice connections. The composite connection detail was a hidden pocket with a conventional fluid grout. The link-slab detail connects the two simple spans of the bridge above the intermediate pier. The bearings under the steel girders at the connection are designed to allow both rotation and longitudinal movement, thus minimizing the negative moments transferred between spans and the forces imparted to the connection. It is expected that, if any cracking were to occur in this detail, then it would be tightly spaced and would limit any water ingress to the structure elements below the link slab.

Figure 6. Illustration. UHPC adjacent box-beam connection detail.



Source: FHWA.

Figure 7. Illustration. UHPC link-slab connection detail on SR962G bridge in Owego, NY, shown as split section.



Source: FHWA.

Abutments

Figure 8 shows adjacent wall segments of a precast concrete abutment that have been connected using UHPC with vertical closure pours. Precast concrete abutment segments have also been connected to piles using UHPC; voids in the bottom of the segments are installed over the piles and then filled with UHPC. Precast semi-integral abutment segments have also been connected using UHPC. An example is shown in figure 9, where a concrete deck is precast on a pair of steel girders and the semi-integral abutment backwall, or a portion thereof, is precast with the deck. The longitudinal UHPC connection at deck level between the modular superstructure segments continues vertically through the abutment backwall. In the case shown in figure 9, the contractor elected to divide the

Figure 8. Photo. Precast abutment wall segments to be connected with UHPC on Rang Saint-Georges Bridge in Quebec, Canada.

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lower portion of the abutment in two pieces to reduce the weight of the modular segments by introducing a horizontal connection through the backwall at about mid-height using UHPC to connect all the pieces in place.

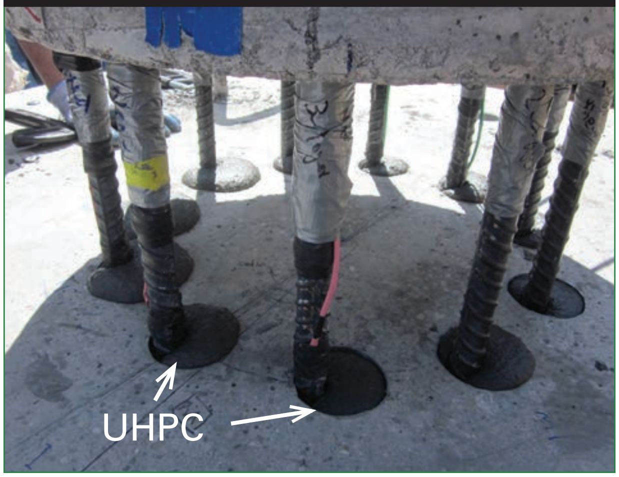
Columns

Durable connections can be made between columns and footings or columns and other elements using UHPC. These connections are typically ducted connections as shown in figure 10. When connecting a new precast component to an existing cast-in-place component, lap splices can also be used. An example of a lap-splice connection is the Hooper Road Bridge in Union, NY, which was completed in 2015 (figure 11) where a precast bent cap was placed on existing columns. The tops of the columns had the vertical rebar exposed over a distance of 12 inches, leaving the core concrete in place. The precast cap had rebar extending downward the same distance. Once the cap was set, UHPC was poured around the rebar to form the connection.

Figure 9. Photo. Semi-integral abutment backwall with vertical and horizontal UHPC connections, I-81 at Preble Road, south of Syracuse, NY.

© 2013 NYSDOT.

Figure 10. Photo. Ducted UHPC substructure connection with column being lowered into footing connection.



Experimental results have shown that the seismic behavior of reinforced concrete columns that are connected to precast cap beams using ducted UHPC connections emulates conventional columns.(33) Research has also shown that full-column plastic-moment capacity can be developed under cyclic loading when using UHPC-filled duct connections. Seismic testing of column-to-footing connections has shown that properly detailed ducted UHPC connections can develop the full ultimate strength of the connected longitudinal bars. Debonding the top portion of the longitudinal bar in ducted connections allows the spread of yielding and prevents premature failure of reinforcements in UHPC-filled duct connections.(34)

Figure 11. Photo. Lap-spliced UHPC substructure connection for Hooper Road Bridge in Union, NY.

Design of Field-Cast Connections

The following section provides guidance for the structural design of UHPC connection details. This guidance is based on concrete materials and structural engineering research that has been conducted on UHPC-class materials. Guidance is provided in the left column while corresponding commentary is provided in the right column.

Development Length of Reinforcement

Guidance	Commentary
The embedment length shall be equal to or greater than the development length.	
The guidance herein may be used for deformed steel reinforcement sizes No. 8 and smaller embedded in field-cast UHPC with 2-percent steel fiber reinforcement by volume and a compressive strength of at least 14 ksi (97 MPa).	A compressive strength of 14 ksi (97 MPa) is defined here to facilitate use of UHPC in accelerated construction when early application of construction loads to newly completed connections is advantageous. The final compressive strength of UHPC is normally significantly higher than 14 ksi (97 MPa).
For minimum cover ≥ $3d_b$, the minimum ℓ_d shall be taken as the following: $8d_b$ for reinforcing bars with yield strength $f_y \leq 75$ ksi (517 MPa). $10d_b$ for reinforcing bars with yield strength 75 ksi (517 MPa) < $f_y \leq 100$ ksi (689 MPa).	Research has demonstrated that deformed steel reinforcement can be developed within comparatively short embedment lengths.[35] An embedment length of $8d_b$ is sufficient for most common reinforcement configurations, including the use of epoxy-coated reinforcement. Increased confinement of the bar and increased mechanical properties of UHPC can allow even shorter development lengths. Bars with higher yield strengths require an increase in the development length.
For minimum cover greater than $2d_b$ but less than $3d_b$, the minimum ℓ_d, shall be increased by $2d_b$.	A decrease in the cover results in reduced confinement of the bar and thus an increase in the required development length.
For concrete bridge deck applications, the minimum development length of a No. 5 deformed steel reinforcing bar with $f_y \leq 75$ ksi (517 MPa) can be taken as the following: $8d_b$ when minimum cover ≥ 1.25 inch (32 mm). $10d_b$ when minimum cover ≥ 1 inch (25 mm).	For No. 5 bars embedded in UHPC with cover as small as 1 inch (25 mm), research has demonstrated that they sustain stress levels comparable with those expected at the ultimate limit state.[36] Using 1-inch cover is common for the bottom mat of bridge deck reinforcing.

No. = number; ℓ_d = development length; f_y = yield strength of reinforcing bars.

Closure Pour Connections Between PBEs

Guidance	Commentary
Connections between PBEs shall be designed to develop the yield strength of the deformed steel reinforcing bars extending from the prefabricated concrete elements.	Development of reinforcing bars can be provided through sufficient embedment length, through bar hoops/hooks/heads, or through mechanical couplers. Given ℓ_d, it is commonly cost effective and practical to develop deformed steel reinforcement through a straight length of embedded bar.
For lap splices of straight lengths of deformed steel reinforcement, the ℓ_s shall be at least $0.75\ell_d$.	Research has demonstrated that passive reinforcement embedded ℓ_d into a connection and spliced with adjoining bars to have a lap of $0.75\ell_d$ can develop stresses in excess of 100 ksi.[35]
Clear spacing to the nearest lap-spliced bar should be less than or equal to ℓ_s. Clear spacing between adjacent bars must also meet the clear spacing requirement defined in Minimum Spacing of Reinforcing Bars.	
Deformed bars extending from precast elements shall be detailed to account for tolerances associated with field installation of components throughout the structure.	
Precast-component interfaces onto which the field-cast UHPC will bond shall be detailed to include female–female shear keys for deck-panel-to-deck-panel installations.	This shear key detail facilitates compression strut transfer of applied loads without relying on dowel action of reinforcing bars. It also can provide added embedment length for reinforcing bars and added interface area for enhanced interface bond.
Precast-component interfaces onto which the field-cast UHPC will bond shall be specified to include roughened interfaces that expose the surface aggregate and shall be specified to be prewetted to saturated surface dry condition. Refer to the section titled Mechanical Properties of UHPC: Interface Tensile Bond Strength.	

ℓ_d = development length; ℓ_s = lap-splice length.

Deck Panel-to-Girder Connections

Guidance	Commentary
The interface connection detail between prefabricated bridge decks and prefabricated girders includes design of the connectors attached to the girder and the design of the remainder of the connection. The design of the connectors attached to the girder shall be completed according to the provisions of *AASHTO LRFD Bridge Design Specifications* 5.7.4 and 6.10.10 with the following exception:[28] Provisions of 6.10.10.1.4 and 5.7.4.2 may be superseded if the following conditions are met: UHPC contains at least 2 percent (by volume) steel fiber reinforcement. The vertical clear distance from top of the girder shear connectors to the bottom reinforcing steel in the deck is less than 3 inches (76 mm). The cyclic shear stress on the minimum shear interface under service loading is less than 0.150 ksi (1 MPa). The static shear stress on the minimum interface shear plane under strength loading is less than 0.750 ksi (5 MPa)	Research has demonstrated that field-cast UHPC with 2-percent (by volume) steel fiber reinforcement is capable of carrying shear stresses through UHPC without the aid of passive reinforcement. This concept allows the elimination of conflict between the deck rebar and the girder shear connectors. An exposed bottom mat of deck reinforcement above the girder line can be engaged by the field-cast UHPC. Shear-stress calculations on UHPC must consider the minimum shear section of UHPC.[30] The minimum shear interface is the controlling interface of all possible failure planes through the unreinforced portion of UHPC.
Interfaces of precast concrete components shall be intentionally roughened to expose the surface aggregate.	Roughening of precast concrete interfaces allows increased UHPC bond at the interface and reduces the local interface shear stresses carried by the discrete steel reinforcement crossing the interface.
Prewetting of interfaces is not required.	The primary mechanism for force transfer between UHPC and the prefabricated deck panel is the panel reinforcing bars that protrude into the UHPC. While prewetting the interface would provide a better bond between the precast concrete and UHPC, it is difficult to do and is not necessary to transfer the shear forces.
Flow of field-cast UHPC within connection details shall be limited to 10-ft (3-m) lengths.	UHPC has been demonstrated to be capable of flowing at least 10 ft (3 m) within a haunch connection detail. Long flow distances around discrete reinforcements can interrupt the dispersion of the fiber reinforcement, which could reduce the mechanical capacity of UHPC.

Ducted Substructure Connection Detail

Guidance	Commentary
Ducted substructure connections shall be detailed to fully develop the ultimate strength of the embedded deformed steel reinforcing bar. Failure modes to consider include bar pullout from field-cast UHPC, duct pullout from conventional concrete, conventional concrete conical failure around duct, and bar rupture.	The development of deformed reinforcing bars commonly used as longitudinal reinforcement in substructure components can be completed in shorter distances when embedded in field-cast UHPC contained in ducted connections. Static and seismic testing has demonstrated the emulative nature of these connections.[37] Tests were completed on field-cast UHPC with 2-percent (by volume) steel fiber–reinforced compressive strengths above 19 ksi (131 MPa), and bar sizes ranging from No. 8 to No. 11. Appropriate detailing of the duct and the surrounding precast concrete are critical to the overall performance of the connection system.
The development length for No. 8 to No. 11 deformed steel reinforcing bars shall be at least $8d_b$. This length is exclusive of any debonded length.	Research has demonstrated No. 8 and No. 11 deformed steel bars can develop a stress exceeding 70 ksi (483 MPa) with $3d_b$ of embedment into a $4d_b$ or less diameter duct.
Ducts must be corrugated and composed of galvanized steel. Duct inside clear diameter (measured on the inside crest of the corrugation) may not be more than $4d_b$.	
Clear spacing between the anchor rod and any portion of the duct wall shall be at least 1.5 times the length of the longest fiber reinforcement in UHPC.	Tight spaces can restrict the flow of UHPC during casting and can impede the uniform distribution of fiber reinforcement throughout the component.
For seismic design, reinforcing bars shall be debonded a minimum of $4d_b$ into each component above and below the component mating interface.	Debonding is necessary to avoid strain concentrations in the precast concrete adjacent to the component mating interfaces under seismic loading.

No. = number.

Minimum Cover and Spacing of Reinforcing Bars

Guidance	Commentary
The UHPC cover around reinforcements or other embedments, the clear spacing between adjacent reinforcements or other embedments, and the minimum thickness of slender volumes of UHPC shall be at least 1.5 times the length of the longest fiber reinforcement in UHPC.	Tight spacing of discrete reinforcements can restrict the flow of UHPC during casting and can impede the uniform distribution of fiber reinforcement throughout the component. When minimum cover and minimum spacing requirements are otherwise satisfied, contact lap splicing of reinforcing bars is acceptable practice.(38)

Mechanical Properties of UHPC: Modulus of Elasticity

Guidance	Commentary
The modulus of elasticity of UHPC may be calculated as follows: $E_c = 49000\ \sqrt{f_c'}$ in psi units (1) $E_c = 1550\ \sqrt{f_c'}$ in ksi units (2)	These equations are based on research results obtained from the testing of steel fiber–reinforced UHPC with compressive strengths between 14 and 26 ksi (97 and 179 MPa).(39) The relationship presented in *AASHTO LRFD Bridge Design Specifications* 5.4.2.4 is limited to concrete strengths below 15 ksi (104 MPa) and should not be used for UHPC because it may overestimate the stiffness of the concrete.(28)

E_c = modulus of elasticity of concrete; f_c' = concrete compressive strength.

Mechanical Properties of UHPC: Cracking Tensile Strength

Guidance	Commentary
The cracking tensile strength of UHPC may be calculated as follows: $f_{t,crack} = 6\sqrt{f_c'}$ in psi units (3) $f_{t,crack} = 0.19\sqrt{f_c'}$ in ksi units (4)	This equation is based on limited research results obtained from the direct and indirect tensile testing of strain hardening steel fiber–reinforced UHPCs with compressive strengths between 12 and 30 ksi (83 and 207 MPa).(6,7,12) The tensile response of a UHPC matrix may develop more rapidly than the compressive response, thus leading to proportionally higher tensile strengths at lower compressive strengths. The cracking and sustained postcracking tensile strengths of the type of strain hardening UHPC formulations commonly deployed in the United States has been observed to be between 800 and 1,200 psi (5.5 to 8.3 MPa). This tensile response is highly dependent on the efficiency of the steel fiber reinforcement.

$f_{t,crack}$ = cracking tensile strength of concrete.

Mechanical Properties of UHPC: Interface Tensile Bond Strength

Guidance	Commentary
Interface surface preparations have a significant influence on interface bond strength. Rough surfaces with ample macro- and micro-texture provide extra bonding area and enhanced bond strength. In order of bond strength from high to low are exposed aggregate interface, sandblasted interface, and as-cast interface.	The interface bond strength can range from the tensile strength of the substrate concrete down to zero. Removing the surface cement paste to provide microtexture is more important than providing macrotexture.[40] Providing macrotexture without microtexture, as occurs with a formliner, is not recommended. UHPC will not bond well to smooth or dirty surfaces.
Prewetting the precast interface with water to a saturated surface dry has been demonstrated to increase the strength of the bond.	Application of bonding agents or adhesives to the precast interfaces may enhance bond strength; however, field application of these substances may present practical challenges that preclude their use.

Physical Properties of UHPC: Density

Guidance	Commentary
The density of UHPC inclusive of the steel fiber reinforcement may be taken as 155 lb/ft^3 (2,480 kg/m^3).	This value most closely represents the density of UHPC with 2-percent (by volume) steel fiber reinforcement. Lesser or greater percentages of steel fiber reinforcement necessarily decrease or increase the density. Inclusion of nonsteel fiber reinforcement also affects the density.

Physical Properties of UHPC: Chloride Ion Diffusion Coefficient

Guidance	Commentary
The diffusion coefficient of UHPC may be taken as 2.0×10^{-10} $inches^2/s$ (1.3×10^{-13} m^2/s).	This value is based on research completed on UHPC cementitious matrices with cementitious materials contents greater than 1,500 lb/yd^3 (890 kg/m^3), no aggregates larger than a fine sand with an average diameter of 0.02 inches (0.5 mm), and water-to-cementitious materials ratios less than 0.25.[38,41–43]

Physical Properties of UHPC: Coefficient of Thermal Expansion

Guidance	Commentary
The coefficient of thermal expansion of UHPC may be taken as 5.6×10^{-6} to 8.3×10^{-6} inches/inch/°F (10×10^{-6} to 15×10^{-6} mm/mm/°C).	The coefficient of thermal expansion value is dependent on the UHPC material constituents and should be tested.[1,44]

Specifying UHPC

Using UHPC requires the development of material and construction specifications. The material specifications define the constituent properties, testing criteria, testing levels, and payment criteria. The construction specifications provide guidance on field-related activities, such as material storage, adequacy of formwork, mixing, in-field testing, placement, and curing.

Common to both the material and construction specifications is the need to identify project-specific criteria that may necessitate alterations to the UHPC formulation, mixing process, placing process, or curing process. Successful UHPC connections require each stage of construction to be completed in a timely and appropriate manner. The owner, the material supplier, the inspectors, and the contractor must work together to ensure success.

Materials Specifications for UHPC

For a public-sector agency, specifying the material portion of UHPC follows either a proprietary- or performance-based method. Regardless of the specification method, the material specification should identify material tests that must be completed in the field and in the laboratory to ensure the UHPC meets project requirements.

To ensure competitive bidding, the Code of Federal Regulations has requirements for using proprietary products on Federal-aid projects.[45] Using a performance specification and providing competitive bidding of patented items with equally suitable unpatented items are examples of practices that are consistent with these requirements. The regulations also provide for using proprietary products as experimental features in Federal-aid projects. Additional information on these requirements can be obtained from FHWA division offices and from the FHWA Construction Program Guide.[46]

Proprietary Material Specification Method

The proprietary method of material specification identifies a list of acceptable products by name. Products are submitted to the agency by suppliers for a particular application, and these products perform according to published literature that is based on previously conducted test results.

In many jurisdictions, a proprietary-based product can be used only if it undergoes the agency's acceptance-testing protocols and is placed on a preapproved materials/products list. Sometimes, an "approved equal" provision is included in the contract plans to allow unidentified suppliers an opportunity to demonstrate whether their product meets the criteria of the contract plans and specifications.

Suppliers are typically responsible for maintaining certifications as prescribed by the agency's procurement criteria.

The following list is not meant to be all inclusive, but it does provide examples of proprietary products with material properties that may align with the needs of a particular UHPC-connection project:

- Aalborg Extreme™ Light 120 (Aalborg Portland A/S).
- BSI® (Eiffage).
- Cor-Tuf® (US Army Corps of Engineers®).
- CRC® (Hi-CON® A/S).
- Densit® (ITW Engineered Polymers).
- Ductal® (LafargeHolcim).
- Dura® (Dura® Technology Sdn Bhd).
- K-UHPC (Korea Institute of Civil Engineering and Building Technology).
- SMART-UP®, formerly BCV® (Vicat).
- Steelike® (Kulish Design Co., LLC).
- Ultra HPC (Béton Provincial).
- UP-F2 Poly® (KING Construction Products).

Note that not all of these products are currently marketed in the United States.

Performance-Based Material Specification Method

Performance-based specifications identify the testing to be performed, performance levels, and sometimes, a set of mixture proportion ranges that a UHPC product must meet. This method of procurement allows for the specification of any proprietary or nonproprietary mix design that meets the performance criteria. The specifying agency must determine all the necessary performance criteria, testing methods, and acceptance criteria. In addition, the agency must be confident that the appropriate UHPC constituents and time needed to perform the tests will be available so the overall schedule of the project will not be affected. Some agencies self-perform or hire independent material testing firms to perform parts or all of the material testing required.

Many universities, often in conjunction with their State's department of transportation, are developing or have developed nonproprietary UHPC mix designs. FHWA published the TechBrief *Development of Non-Proprietary Ultra-High Performance Concrete for Use in the Highway Bridge Sector* to assist with the creation of UHPC mix designs.(47)

In a performance-based specification, it would not be appropriate to specify a strict set of mixture proportions. In addition, it is typically not recommended to do so for UHPC because proposal of proprietary products is likely, and the constituent details of those mixes may not be known to the proposing entity. However, these criteria may be necessary, at least within defined proportion ranges, to prevent inappropriate products from being proposed to the agency.

Examples of mixture requirements that could be included in a UHPC performance-based material specification include the following:

- Water-to-cementitious materials ratio < 0.25.
- Portland cement content ≥ 1,000 lb/yd^3 (593 kg/m^3).
- Maximum aggregate size ≤ 0.25 times the fiber length.
- Maximum aggregate size ≤ 0.125 inches (3.2 mm).
- Steel fiber–reinforcement geometry, strength, and volume percent.

Prescriptive Mixed-Material Specification Method

A prescriptive mixed-material specification is a potential option to avoid some of the complexity of performance-based material specifications and the limitations on sole sourcing products in a proprietary material specification. This method gives the option of one or more specified nonproprietary UHPC mix designs alongside one or more proprietary UHPC products. The biggest challenge with this method is selecting a nonproprietary mix design that has all of the required material properties, has been demonstrated to work, and uses ingredients that can be readily obtained by a contractor. As noted in the section titled Performance-Based Material Specification Method, many universities are working on nonproprietary mix designs that might be suitable for a prescriptive mixed-material specification.

Material Performance Testing: Laboratory and Field

Identification of material performance tests and acceptance criteria is highly recommended. They provide a means to assess the properties of a particular UHPC mix design and can validate the appropriateness of material characteristics to the intended needs of a project. Some material performance tests are appropriate for completion in the laboratory before the construction of a project, but other tests are performed during construction.

In June 2017, ASTM published standard ASTM C1856/C1856M, Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete.(9) Many of the UHPC material property tests conducted are well-established tests used for conventional concrete with modifications or exceptions needed to apply these tests to UHPC. Thus, ASTM C1856 references other existing ASTM test procedures and then simply adds the required procedural modifications for UHPC. Table 2 describes commonly recommended material tests, test frequency, acceptance criteria, and the stage of project delivery when they are often conducted.

Test Method	ASTM	Material Vetting	QA/QC	QA/QC Frequency	Acceptance Criteria
Flow	C1856 (C1437 mod.)	Yes	Yes	Once per mix	• Flow range from 7 to 10 inches (178 to 254 mm).
Compressive strength	C1856 (C39 mod.)	Yes	Yes	At least once per 25 yd^3 (19 m^3) or once per 12-hour shift	• >14 ksi (97 MPa) after 4 days.[a] • >17.5 ksi (120 MPa) after 28 days. • >14 ksi (97 MPa) before application of construction or live loads.
Chloride ion penetrability	C1856 (C1202)[b]	Yes	Not common	N/A	• ≤500 coulombs by 28 days.
Freeze–thaw resistance	C1856 (C666A mod.)	Yes	Not common	N/A	• RDM ≥ 90 percent after 300 cycles.
Shrinkage	C1856 (C157 mod.)	Yes	Not common	N/A	• ≤800 microstrain at 28 days. • Consider curing scenarios.

Table 2. Material tests commonly applied to UHPC used in field-cast connections.

QA/QC = quality assurance/quality control; N/A = not applicable; RDM = relative dynamic modulus of elasticity.

[a]14 ksi is the strength at which UHPC is mature enough to be fully loaded and at which the rebar development length equations are applicable. The 4-day limit can be shortened if desired to accelerate construction by applying heat and accelerators.

[b]While ASTM C1856 says that test method C1202 is not applicable to UHPC mixtures with metallic fibers, many mixtures with metallic fibers can, in fact, be successfully tested using method C1202.(9) Some mixtures, especially those with longer fibers that touch each other, cannot be tested using method C1202. In those cases, a permeability test such as ASTM C1543 may be considered, with the results compared against the permeability of a highly durable conventional concrete.(48)

The manufacturer of the steel fiber reinforcement should provide documentation indicating the chemical composition, the tensile mechanical properties, and the geometry of the fibers. Samples may be retained during construction for future analysis if there are any questions about the properties of the fibers.

Flow Tests

Rheological properties describe the flow characteristics of a given UHPC mix design. It is important to quantify these properties because an overly stiff mix may not allow the UHPC to flow into the connections, but an overly fluid mix can result in the segregation of the steel fiber reinforcement to the bottom of the pour.

ASTM C1856, which modifies ASTM C1437 (figure 12), is used to determine the appropriate rheological properties for UHPC.(9,19) The test is a miniaturized version of the spread test used for self-consolidating concrete. The procedure

Figure 12. Photo. ASTM C1856 (C1437 mod.) flow test on UHPC.(25,9)

Source: FHWA.

only tests the static spread of UHPC and does not involve table drops. At the conclusion of this test, UHPC can also be assessed for fiber distribution and matrix segregation.

Flow tests conducted in the laboratory establish the acceptable spreads for a given project application and can be used to determine the sensitivity of the mix to constituent and environmental variations. These laboratory tests can also help establish acceptable ranges of constituent variations if they are needed during construction.

During construction, flow tests are conducted immediately after mixing to assess the mix before placement. Testing may also occur during placement operations to address environmental changes that may influence the mix and to assure consistency among batches.

The degree of variation in flow should be within the prescribed ranges established from previously conducted laboratory tests. Adjustments to mix constituents or mixing processes to address environmental conditions (impacting setting times) may be necessary; however, any changes should be consistent with guidance provided by the material supplier and/or developed during preliminary testing. Variations in constituents may include minor modifications to the amount of water and/or superplasticizers. For example, in hot weather, it is common to batch UHPC with flow at the higher end of the flow range to allow more working time, and in colder weather, it is preferable to batch UHPC with the lower end of the flow range to reduce any potential for fiber settlement from construction vibrations during longer setting times.

Compression Tests

Similar to conventional concrete, compressive strength testing is performed on UHPC to indicate the compressive response of the material. ASTM C1856 references the standard concrete cylinder compression test, ASTM C39, with minor modifications.(9,10) Because of the high strength of UHPC, an accelerated loading rate of 145 psi/s (1 MPa/s) is specified to allow expedited testing without adversely affecting the observed response.(49)

All cylinders shall have both ends ground such that the ends do not depart from perpendicularity to the axis by more 0.5 degrees, and the ends are planar to within 0.002 inches (0.050 mm).(9) 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.

It should be noted that ASTM C1856 requires 3-inch (76-mm)-diameter by 6-inch (152-mm)-long cylinders to determine the compression strength of UHPC.(9) These reduced-size specimens save on material use, reduce waste, simplify the handling and transport of specimens, and allow the use of smaller-capacity compression-testing equipment without any significant variation in results compared to full-size cylinders.(49) Typically, at least three cylinders are tested for each test condition to determine an average indication of strength. If laboratory testing is used to determine the curing behaviors of field-cast connections, then the cylinders should be match cured in a manner that is similar to the anticipated in-field conditions.

Cylinders are typically tested for two different compression strength criteria. The first criterion is a compressive strength of 14 ksi (97 MPa). This strength is when the rebar development length criteria given in this document are valid and, thus, when comparable UHPC connections may receive construction or live loads. The second criterion is the 28-day compressive strength, given as a minimum of 17.5 ksi (120 MPa). This strength is important in demonstrating that UHPC has fully matured and as an indicator that the expected durability properties have been obtained.

Construction Specifications for UHPC

In-field activities related to the storage, mixing, and placement of UHPC are often detailed in the construction portion of UHPC specifications. Some specifications require contractors to demonstrate competence with the mixing and placement of UHPC materials before the start of actual work. Construction specifications may include trial mixing; specification of the order and manner of constituent mixing, mixing equipment, placement, testing, adequacy of formwork, and bond surface preparation; and demonstration of appropriate staffing and equipment. For proprietary UHPCs, specifications typically require that a supplier representative be onsite during UHPC mixing and placing operations. These construction specifications may also prescribe curing methods, onsite material storage, and material-usage timeframes (i.e., expiration dates).

A more detailed construction checklist that has been published by FHWA, *Example Construction Checklist: UHPC Connections for Prefabricated Bridge Elements*, can be found on FHWA's website.[50,51] The checklist identifies items that should be considered as the construction process for a UHPC-connections deployment is developed.

In locations where UHPC connections have been previously deployed, the construction community has generally developed the necessary skill set through a willingness to modify normal construction processes according to past experience and expert advice. The following information is provided as an introduction to some common aspects related to the construction of field-cast UHPC connections. Material testing that occurs in the field is discussed in the section titled Material Performance Testing: Laboratory and Field

Surface Preparation for Bond

The preparation of surfaces where the precast component bonds with the field-cast UHPC is critical to ensuring durability and long-term performance of the system. Lack of bond allows water infiltration and potentially accelerates the degradation of the concrete and embedded rebar. UHPC can bond exceptionally well to conventional concrete at connection interfaces; however, the bond strength is highly dependent on the surface preparation of the precast concrete. Similar to other cementitious materials, UHPC is not likely to form a strong bond with smooth, dry, precast concrete. A better bond is achieved with a surface exhibiting micro- and macro-texture. Good bonding has been obtained by casting UHPC against a precast concrete element with an exposed aggregate finish. An exposed aggregate finish can be created by applying a gelatinous retarder to the formwork in locations where the finish is desired. The hydration reaction of the fresh concrete contacting the retarder is delayed. After form removal, the unhydrated paste can be washed from hardened concrete with water. This process is similar to that sometimes used to create an architectural finish on a precast panel; however, here, it is used to create a structural bonding surface. An example of this type of surface finish is shown in figure 13 along with a sandblasted surface finish and a steel-form surface finish. Other examples of the exposed aggregate surface finish are shown in figure 22 and figure 33.

It is also important to remove contaminants from the precast concrete surface. The concrete substrate should be free of materials or substances (contaminants) that inhibit bond with UHPC. Contaminants should be removed prior to placing UHPC. Contaminants that reduce bond strength include dust, dirt, grit, grease, and form release agents.

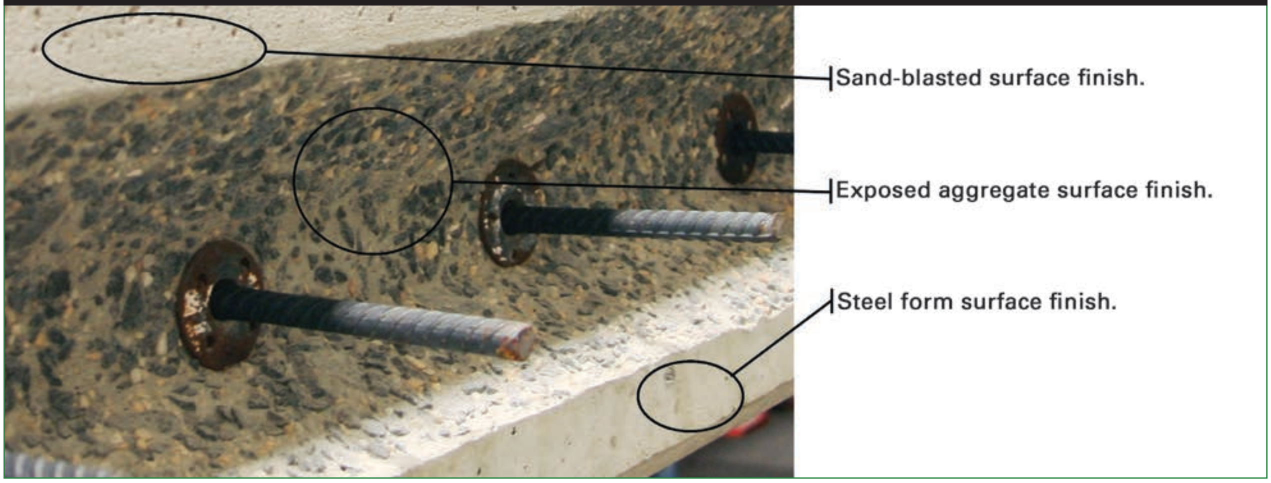
Prewetting the precast concrete interface to a saturated-surface-dry (SSD) condition immediately before UHPC is placed also improves bonding because it eliminates the dehydrating effect that occurs when dry concrete extracts water from the newly placed UHPC.

It is preferable to obtain a well-bonded interface through the normal UHPC connection construction process than to implement remedial solutions to seal unbonded areas. For this reason, it is helpful to encourage the use of construction processes that are likely to result in fully bonded interfaces.

Specifications to promote a good bond might include language speaking to the following qualities:

- A roughened surface on the precast concrete component with current best

Figure 13. Photo. Exposed aggregate surface finish on a precast concrete component.[25]



Source: FHWA.

practice providing an exposed aggregate finish.

- Cleaning of substrate surfaces to remove any contaminants from the substrate surface.
- The wetting of a precast surface to an SSD condition immediately before UHPC placement.

Owners may consider including a section in their UHPC specification to address the following issues:

- Construction activities that promote good bonding such as those mentioned above.
- Methods to assess bond performance such as completing a water-tightness test on a bridge deck.
- Remedial solutions if the bond is found insufficient, such as specifying a sealing procedure for any identified unbonded areas.

On occasion (such as when precast UHPC elements are being connected with field-cast UHPC or when a construction joint is needed in the field-cast UHPC), fresh UHPC needs to be poured against cured UHPC. Because of the lack of aggregate and lack of porosity of UHPC, for fresh UHPC to bond to cured UHPC, the surface of the cured UHPC should be roughened to expose steel fibers. A good way to obtain the desired surface is to use set retarders on the formwork in the same manner one would with conventional concrete to achieve an exposed aggregate finish. Hardened UHPC can be roughened through the use of mechanical chipping. Bonding agents can also be considered.

Formwork

Fresh UHPC is a fluid, self-consolidating material that contains little or no coarse aggregate. Because of these features, the formwork used to contain the material requires tighter control than the formwork used for conventional concrete. UHPC also places higher pressures against the formwork compared with conventional concretes. Formwork that will be in contact with UHPC should have a nonabsorbing finish; otherwise, the formwork will pull moisture out of the UHPC.

Success or failure of UHPC placement is directly related to contractor and construction inspector attentiveness to ensuring that the formwork is properly sealed and capable of resisting the hydrostatic pressures from UHPC in an unhardened state. Some contractors have gone so far as to temporarily fill connection forms with water to ensure leak tightness and to validate pressure resistance. Although not necessary, this activity can prove beneficial as a learning tool.

As is common with fluid materials cast into enclosed spaces, trapped air must be provided an exit so that the space can be filled by UHPC.

Small amounts of air trapped in UHPC and in connection spaces during placement can result in the void space initially appearing to be filled with UHPC, which later subsides slightly as the air escapes. To address the subsidence, forms are typically constructed to allow a little overfilling of the connection and may include features to provide a slight pressure head on the pour after it is placed. Some agencies do not overfill connections between longitudinal structural members, such as box beams and deck bulb tee girders, to avoid grinding the excess. These agencies find the subsistence is not detrimental, and an overlay is often placed on top to help obtain final grade. Even if the connections are not overfilled and grinded, however, the tops should still be mechanically roughened to remove a weak UHPC crust and laitance that is often present at the top of top-formed UHPC.

An example of these details can be seen with precast deck panel connections that use UHPC. Wood strips are frequently installed on either side of the top of the connection to allow overfilling. As is done with grout, UHPC is placed starting from the low end of the pour. The formwork is capped at the low end to prevent the material from escaping as subsequent material is placed into the joint. In nearly all cases, the formwork has a "chimney" to address any subsidence effects from the release of air as described earlier. The chimney also sustains a slight pressure head on the unhardened UHPC material to ensure that the connection space remains completely filled. Figure 14 shows the filling of a bucket that serves as the overpressure source for a connection space that has been filled. The bucket is attached to the top form, and both contain a hole allowing UHPC to flow into the connection as needed.

It can be advantageous to include formwork features on the prefabricated components to lessen the demand for field-installed formwork. For example, detailing deck panels or decked girders to include extended concrete "lips" at the bottom of the deck-level connection can eliminate the need for under-connection formwork and can simplify field-construction activities by allowing for top–down construction.

Figure 14. Photo. UHPC placement into a bucket that serves as the overpressure source for a connection.[25]

Source: FHWA.

Bulkheads

Bulkheads are typically used to limit the size of connection pours since overly large connection pours are difficult to fully fill. This construction process also limits the amount of UHPC at risk of being lost if there is a form blowout. The most common material for bulkheads is plywood that is removed after the first pour has hardened. Acrylic sheeting (plexiglass) has also been used as a stay-in-place bulkhead.

If a removable bulkhead is used, there will be a cold joint between adjacent pours of UHPC at bulkhead locations. The self-consolidating nature of UHPC and head pressure will make the joint tight but will not completely preclude the possibility of water infiltrating the joint. Reinforcing steel is not typically placed inside and parallel to UHPC connections. Thus, there is usually no reinforcing steel crossing the bulkhead locations, and as a result, if any moisture infiltrates the joint, it will not cause any corrosion to deck reinforcing steel. Corrosion concerns can be further minimized by ensuring bulkheads are not located above steel framing members. The bulkhead locations can also be sealed if necessary as part of a watertight integrity procedure that some agencies perform on precast bridge decks that are not overlaid.

Mixing

As with any prebagged cementitious composite, UHPC must be mixed according to the specifications. For UHPC, these specifications commonly provide information on the constituent volumes and the order and timing needed to mix the material. UHPC is sensitive to mixing deviations, so the timing and mix proportions must be followed. The addition of water or chemical admixtures above or below previously established ranges can be detrimental to the early and long-term performance of the material.

Weather conditions can also affect the properties of UHPC before and during the mixing operations. The temperature of UHPC increases during mixing, and some mix water is lost because of evaporation. Best practices call for the mixing operations to occur under cool temperatures and away from direct exposure to sun and wind. Maintaining a reduced temperature of 50 to 60 °F (10 to 16 °C) on stockpiled materials and mix water is also advantageous on warm days. The fluidity of UHPC can become reduced, decreasing the time available for placement, 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 operations occur during warm weather conditions.

UHPC can be mixed in most concrete or grout mixers. The mixer must be capable of dispersing the liquids uniformly within the powder matrix, with higher-efficiency mixers completing this task more efficiently than lower-efficiency mixers. Both tow-behind pan mixers and conventional concrete ready-mix trucks have been used to mix UHPC; however, high-shear mixers can be desirable because they can significantly increase the efficiency of the mixing process. As a rule of thumb, the maximum volume of UHPC that can be mixed in any of these mixers is approximately between 1/3 and 2/3 of the volume capacity of the mixer.

The mixer type and the number of mixers should be determined based on the rate of UHPC delivery required for the project. Figure 15 shows a portable concrete pan mixer preparing UHPC that was used in the field-cast connections for the Keg Creek Bridge in Council Bluffs, IA.

Figure 15. Photo. Portable concrete pan mixer preparing UHPC for placement during the construction of the field-cast connections.

Source: FHWA.

Field-cast connections on short- to medium-span bridge projects may require 10 yd^3 (7.6 m^3) or more of UHPC. Commonly deployed mixers can mix only a fraction of this volume per batch.

Most UHPC connection details need to be divided into smaller sections using removable bulk-heads so that the mixing and placement rates allow UHPC connections to be filled uniformly. Like with conventional concrete or grouts, this requirement controls the locations of any cold joints within the mass of field-cast concrete.

Placing

Traditionally, the conveyance of UHPC from the mixer into the field-cast connection has been through motorized or nonmotorized wheelbarrows or buggies. Individual connections are filled consecutively. It is possible to pump, augur, or chute UHPC; however, these methods should be demonstrated in advance, through a field prototype, and be carefully coordinated to ensure appropriate delivery of the material to the connections. Figure 16 shows UHPC placement on a bridge in Lyons, NY.

Pumping UHPC can be problematic and is not recommended in most situations. With proper adjustment of the mix, UHPC can be pumped successfully in cool weather. However, as the ambient temperature rises, the pumped UHPC is highly vulnerable to overheating due to the combination of pump pressure, friction in the hose, and the hose's exposure to the sun. When the temperature of UHPC exceeds 80 °F (27 °C), the UHPC will likely lose its workability, will not self-consolidate in the connection, and will be at risk for being discarded.

Because deck-level UHPC connections are fully exposed to the weather during casting, the leading exposed surface of the pour can desiccate and crack before the void space is completely filled and the connection is covered. Often, these deck-level connections are subdivided in a manner that is determined by the speed with which the mixing and placement can occur. UHPC should be transported, placed, and covered as quickly as possible to minimize

Figure 16. Photo. Longitudinal connections cast between deck-bulb-tee girders on Route 31 bridge in Lyons, NY.

the potential for reduced flowability into the connection and avoid loss of mix water from exposed surfaces. In hot weather, it is common to batch UHPC with a flow at the higher end of the flow range to allow more working time, and in colder weather, it is preferable to batch UHPC with the lower end of the flow range to reduce any potential for fiber settlement from construction vibrations during longer setting times. Working times or pot life can vary from less than 15 minutes with fast-setting mixes in hot weather to several hours for slow-setting mixes in colder weather. Methods to estimate conventional concrete surface dehydration rates are available and can be used by the UHPC supplier, contractor, and construction inspection personnel to tailor the placement process.[52]

When two "heads" of adjacent UHPC pours meet one another, an interface is formed, and there is limited interface crossing by the fiber reinforcement. This situation can be avoided by prescribing that all succeeding UHPC placements should be poured into previously placed, fluid UHPC.

It is rare for UHPC to require vibration to fill the area being cast. UHPC should not be internally vibrated because of the detrimental impact that this type of vibration has on the fiber reinforcement (i.e., it may settle to the bottom of the pour). External vibration is commonly impractical because of site conditions. Rodding is acceptable and is sometimes used in situations where two successive pours meet. Tapping with a hammer on the top form surface can help remove entrapped air in the connection and provide an audible quality-control check.

Finishing

Traditional concrete finishing practices are not used on field-cast UHPC. The low water-to-cement ratio and high supplementary cementitious content virtually eliminate bleed water from the surface of the concrete. Because of these limitations, alternate techniques must be used to ensure an appropriate concrete surface. UHPC is typically placed in a closed form, or the form is closed immediately after placement. The closed form should be designed to allow full filling of the connection space without trapping air. Small-diameter bleed holes can be drilled into the top form to aid with the removal of entrapped air. On flat surfaces exposed to air, UHPC should be in contact with the top formwork to minimize surface dehydration. For horizontal surfaces that are visible to the public, the connection is frequently overfilled (see Formwork section). This process allows the UHPC surface to be ground to match the adjacent prefabricated surfaces.

Curing and Strength Gain

To reduce the risk of surface dehydration, UHPC should remain sealed from exposure to the external environment until attaining a compressive strength of at least 10 ksi (70 MPa). UHPC may be (but does not need to be) moist cured beyond a strength of 10 ksi (70 MPa) because of the low permeability of the cementitious matrix. Also, UHPC should not freeze before attaining 10 ksi (70 MPa) of compressive strength.

UHPC-class materials can exhibit long dwell times before the start of initial set. After initial set has occurred, strength quickly develops. The timing of initial set is dependent on the temperature of UHPC at time of placement, the temperature conditions surrounding the material, the admixtures included, and the cement type used. Although cooler temperatures are beneficial for mixing and placing UHPC, warmer temperatures are beneficial to initiate the initial set. In addition, a minimum curing temperature of 60 °F (15 °C) until after initial set has occurred is recommended to reduce the potential for fiber settlement and segregation.

Supplemental heat can be provided to the UHPC and the surrounding prefabricated elements to reduce initial set times and accelerate strength gain. This heat can be supplied externally (e.g., ground heating mats) or internally (e.g., resistance heating wires). To prevent the extraction of moisture from the mix, heat sources that use forced air should not be applied to exposed surfaces of freshly poured UHPC.

As with any field-cast grout, construction activities that induce relative movement into connections before the grout is set can weaken the connection. These relative movements can reduce the capacity of embedded connectors by decreasing the bond with grout. This topic is of particular relevance in the staged construction connections that are sometimes used during bridge deck rehabilitations. Ideally, relative movements should be minimized until UHPC has attained 14 ksi (97 MPa) of compressive strength.

Formwork may be stripped after UHPC reaches a compressive strength of 14 ksi (97 MPa). This strength level typically occurs within 2 to 4 days, depending on ambient temperatures, after pouring. If accelerators and/or heat are added to the in-situ UHPC, UHPC can reach a compressive strength of 14 ksi (97 MPa) in as little as 12 hours. Cementitious reactions continue to occur as the full mechanical and durability properties are achieved; however, UHPC may be exposed to the environment without experiencing any deleterious effects. The structure may be subjected to construction and/or traffic live loads after a compressive strength of 14 ksi (97 MPa) is reached.

Surface Profiling

Horizontal field-cast UHPC surfaces, such as the exposed surfaces of precast deck panel connections, must be profiled for rideability if no overlay is used or to facilitate placement of an overlay. When an overlay is not used, the top face of the precast concrete deck component can be designed with a sacrificial surface that is profiled after installation and connection casting so that the resulting deck surface has a uniform profile. When overlays are used, the UHPC connections are typically ground flush with the precast deck panels to facility placement and future replacement of the overlay.

Grinding and grooving operations of field-cast UHPC connections (and surrounding precast component decks) have been successfully completed on prefabricated bridge deck projects. Some contractors have reported that grinding and grooving are easier if completed before UHPC reaches its full compressive strength (typically grinding and grooving is started when UHPC attains 14 ksi (97 MPa)). The ease with which these operations can be completed depends on the UHPC strength, the UHPC formulation, and the type of grinding and grooving equipment deployed. Figure 17 and figure 18 show two methods of surface profiling bridge decks on interstate highways.

Figure 17. Photo. Surface profiling of a bridge deck on I-690 near Syracuse, NY.

© Lafarge North America.

Figure 18. Photo. Surface profiling of a bridge deck on I-81 near Syracuse, NY.

© Lafarge North America.

Construction Engineer Inspection

The monitoring of construction activities is a critical part of the deployment of field-cast UHPC connections. As with any phase of a bridge construction project, this phase requires close attention to the process and the generation of appropriate documentation. The construction engineering inspector must be familiar with the overall construction process as well as specific differences associated with the deployment of this technology compared with conventional grouts and concretes. Some examples of specific items to consider are as follows:

- **Familiarity with specification for UHPC and any other relevant special provisions.** The inspector must understand the documentation associated with the project and must use it as the framework through which the field construction activities are completed.
- **Worker safety equipment and procedures.** The inspector must be familiar with safety precautions relevant to the deployment of UHPC in this type of construction project. In particular, the powdered constituents of UHPC are exceptionally fine and can become airborne more easily than traditional portland cement. Also, the steel fiber reinforcement commonly has a very small diameter and, if handled incorrectly, can lead to punctures of clothing, safety equipment, and skin.
- **Prior coordination of construction activities.** Construction projects of this type commonly include coordination activities before the initiation of the construction process. These coordination activities may include practice batching, mixing, and placing of UHPC either on or adjacent to the site by the construction crew that will thereafter be completing the UHPC connections. Testing all relevant equipment immediately before the start of construction activities is also important.
- **Lot numbers, dates, and storage of constituent materials.** The inspector must ensure that the constituents are tracked before use and that relevant details are recorded at the time of the use of the constituents. Also, the constituents must be stored appropriately to avoid degrading the products before use. This step is particularly important to avoid any unintentional hydration of the UHPC cementitious composite before the initiation of mixing.
- **Mixing process, including weighing, timing, and discharge.** The inspector must ensure that the proper constituents are added to the mixer within the predetermined proportion ranges and timeframes. The mixing operation should be timed because the mix time across batches provides an indication of the consistency of the product being delivered. The temperature at discharge is also an indicator of consistency and, if too high, can be an indicator of likely future placement difficulties.
- **Formwork considerations.** Forms for field-cast UHPC must be tighter than normal because of the rheology of UHPC. Common remedies for formwork leakage are less effective because of the rheology of UHPC. Long connections are commonly divided into smaller length spaces in order to allow for rapid filling and closure of individual connections.
- **Surface preparation.** The precast concrete surfaces against which UHPC will be cast must be appropriately prepared to achieve the desired bond performance. The inspector should ensure that the interface surfaces meet the construction requirements for roughness and that they are free of foreign materials. Prewetting of these surfaces to an SSD condition immediately before UHPC placement is commonly specified and must be monitored by the inspector.
- **Field test methods for assessing fresh properties.** The inspector must be familiar with ASTM C1856/C1856M, Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete, the test methods used to assess the fresh properties of UHPC. The inspector must ensure that the tests are completed correctly and at appropriate times and that the test results are recorded.[9]
- **Pour locations and volumes per pour location.** The inspector must ensure that the construction process follows the recommended practice regarding UHPC volumes per connection location. Overly large connections result in difficulty bringing any one connection space to a fully filled condition. The inspector must

be aware of pour locations, connection geometry, and pour volumes to ensure that the UHPC connections are being filled in an appropriate, sequential, and timely fashion.

- **Placement of UHPC.** UHPC should be placed into each connection space without the use of vibration. Vibration can cause disruption in the dispersion of the steel fiber reinforcement. If placed through discontinuous pours, successive additions of UHPC should be poured into fresh, previously placed UHPC. UHPC can be rodded at locations where successive pours meet.
- **Form closure requirements, including over pressure.** The inspector must monitor the process as each connection space is filled and any top forms are installed. UHPC can subside because of either continued flow into unfilled areas or release of entrapped air. Full filling plus overpressure from a chimney is commonly recommended and thus must be monitored.
- **Curing requirements.** The inspector must ensure that the field-cast UHPC is cured appropriately to develop material properties in a reasonable timeframe.
- **Surface preparation of hardened UHPC.** Uppermost UHPC surfaces within a connection space, such as the top connection surface on a bridge deck, commonly require dressing to create an appropriate surface profile. This step may include grinding and grooving. These operations are easier to complete after UHPC has hardened and before it has gained its full strength. Early dressing can result in tearing of UHPC, and late dressing can unnecessarily cause wear to the dressing equipment. Inspectors should monitor the timing of these operations.

A detailed construction checklist, including items related to construction inspection, has been published by FHWA. *Example Construction Checklist: UHPC Connections for Prefabricated Bridge Elements* can be found on FHWA's website.[50,51]

Case Study: Construction of I-81 Bridges in Syracuse, NY

NYSDOT is a leader in the deployment of innovative solutions that use field-cast UHPC connections. After constructing dozens of bridges using UHPC, the design and construction community is growing more familiar with this material and is finding new ways to use it. This familiarity has led to many successful projects and new ideas that improve design, fabrication, and construction efforts needed for bridge construction. This section describes a case study on four interstate bridges recently constructed near Syracuse, NY, that use UHPC details, precast full-depth deck panels, no post-tensioning, and no panel-leveling screws. The four bridges, which are on I-81, were rapidly redecked using precast concrete deck panels and field-cast UHPC connections. One pair of bridges spanned East Castle Street, and the other pair spanned East Brighton Avenue. NYSDOT chose to reconstruct the decks of the two bridges on the southbound alignment using a 10-day closure and then repeat the same accelerated process for the northbound structures.

All four bridges have steel superstructures that were being retained while their decks, parapets, and approach slabs were replaced. Figure 19 shows one of the bridges after the demolition of the existing deck and before the installation of the new precast deck panels. The steel shear studs were installed along with the cold-formed steel angles that serve as the haunch formwork.

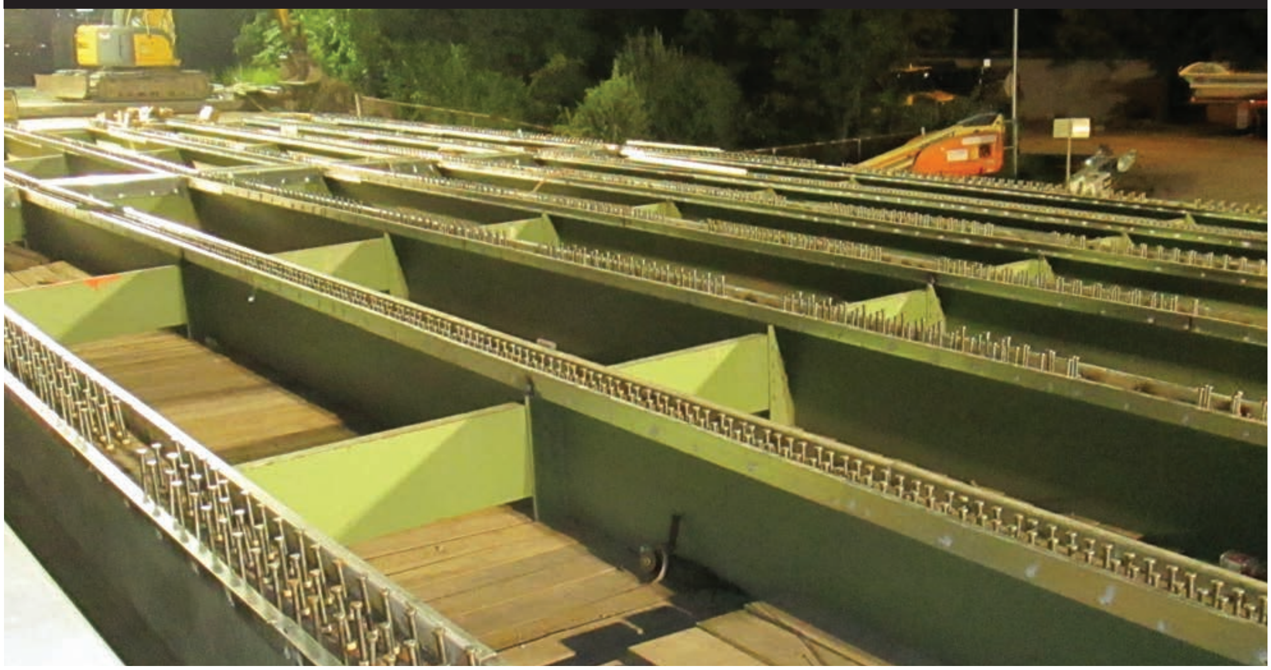
The next phase of the deck reconstruction is the installation of the precast deck panels and precast approach slabs. Figure 20 shows one of the deck panels being lifted from the truck. This panel spans transversely across the bridge between the interior girders of the bridge.

Figure 21 shows the installation of a deck panel that spans over the exterior girder and first interior girder. The panels from figure 20 can be seen just to the left of the first interior girder line.

Note that the barrier has been cast integral to the panel shown in figure 21. These exterior panels were fabricated upside down. This method of fabrication offers benefits to the owner and the contractor (e.g., the top of the deck and the parapet are composed of high-quality, well-consolidated concrete).

The connection details used in this reconstruction project use the field-cast UHPC connection concepts presented in the section titled Common UHPC Connections. The connection details between the precast panels use a non-contact lap splicing of straight lengths of epoxy-coated reinforcement embedded in UHPC. This detail is shown in figure 22. Note that exposed aggregate surface was used to increase the bond at the mating surfaces.

Figure 19. Photo. Superstructure prepared for precast panel installation.[25]



Source: FHWA.

Figure 20. Photo. Transport and rigging of precast deck panel.[25]

Source: FHWA.

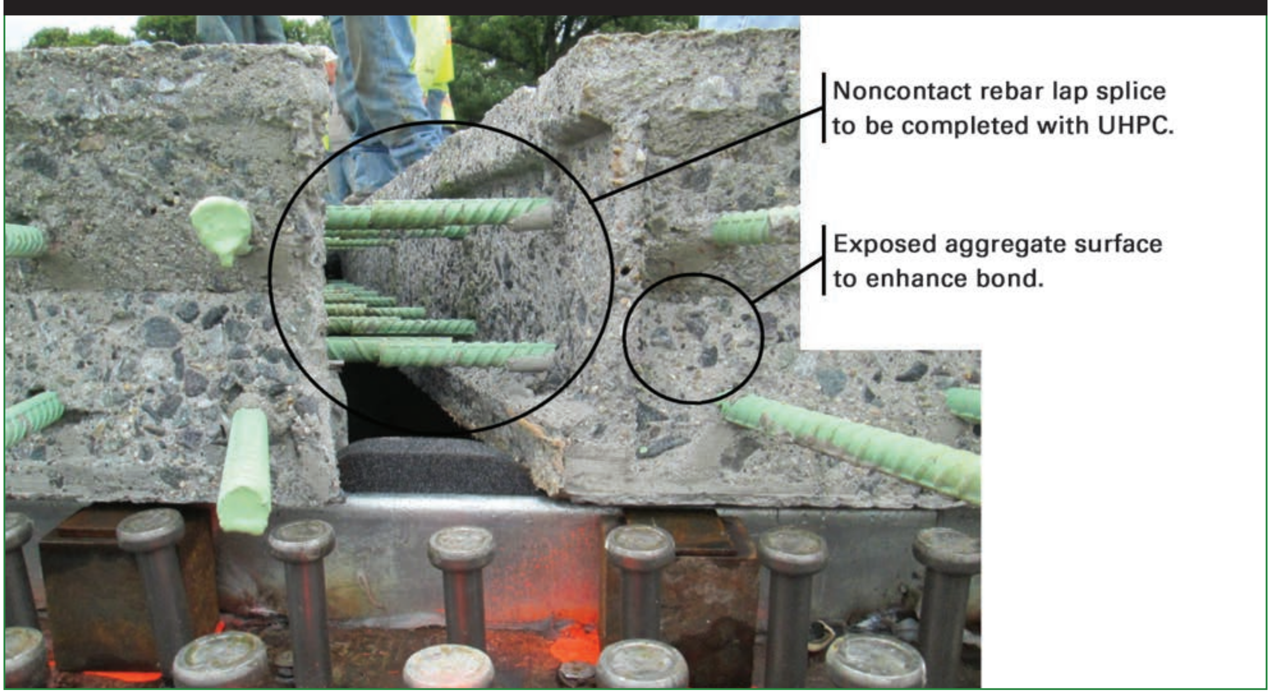
The deck-to-girder connections above the first interior girder also use a field-cast UHPC connection detail, shown in figure 23. The detail at this location combined the deck-level connection with the deck-to-girder connection in a unique way that facilitated construction and maximized the value of UHPC.

A hidden-pocket composite connection detail was used above the other girder lines on these bridges. Although this detail was forced to use conventional grout because of now-superseded Buy America provision-related constraints, the connection details do demonstrate a concept worthy of note.[45,24] Figure 24 shows the bottom

Figure 21. Photo. Installation of precast panel with integral barrier.[25]

Source: FHWA.

Figure 22. Photo. Deck-level connection between precast deck panels.[25]



Source: FHWA.

mat of reinforcement in the deck panel and the exposed aggregate surface that is used to improve the interface bond. Because this detail uses conventional grout, the shear-stud heads are required to extend above the bottom mat of reinforcement as shown in figure 25. As discussed in the section titled Deck Panel to Girder—Composite Action, the embedment of the shear studs above the bottom mat would not need to occur if UHPC had been used in the connection. This detail can be seen in figure 4 and in figure 23. Finally, figure 26 shows the

Figure 23. Photo. Longitudinal connection detail above first interior girder line with shear studs stopping below the bottom mat of rebar.[25]

Source: FHWA.

Figure 24. Photo. Connection detail on underside of precast deck panel.[25]

Source: FHWA.

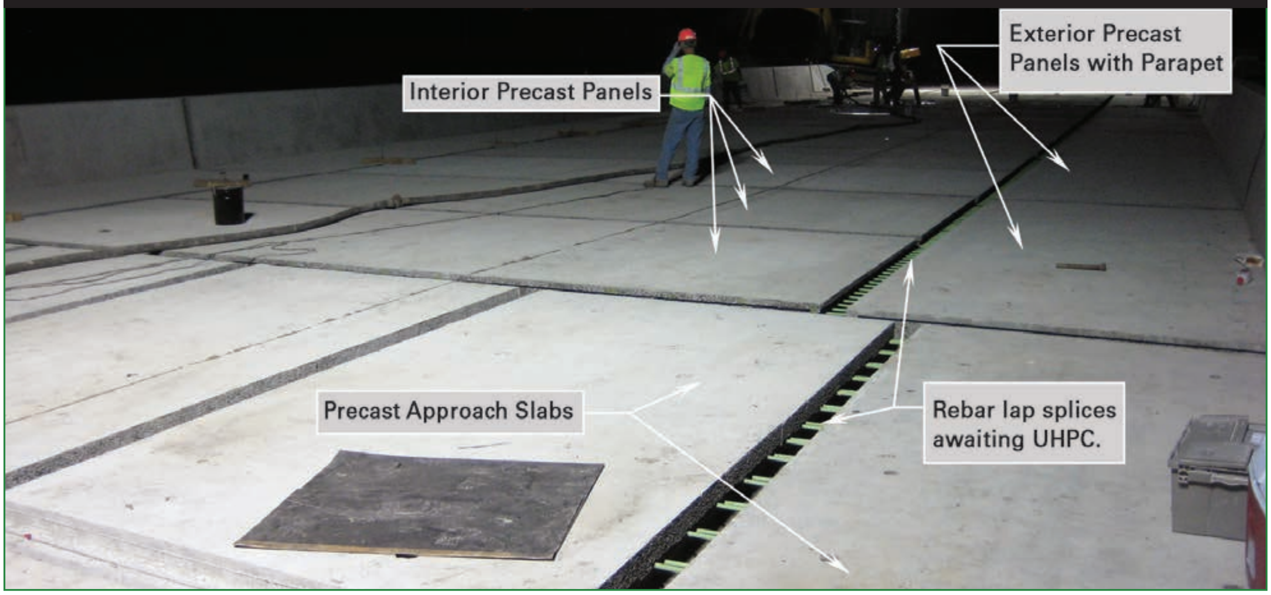
Figure 25. Photo. Hidden pocket connection detail with shear studs extending above the bottom mat of rebar to allow use with non-UHPC grouts or concretes.[25]

Source: FHWA.

bridge deck after all of the panels have been installed.

The mixing, transport, and placement of UHPC into the connections for each bridge deck was completed over the course of a few hours, as shown in figure 27 and figure 28. The UHPC was mixed adjacent to the bridge site in a pair of mixers that alternately discharged approximately 0.65 yd^3 (0.5 m^3) of UHPC. Motorized buggies transported the UHPC to the connections. The UHPC was then poured into the connections until the local area was filled. The filled connection was then covered with

Figure 26. Photo. Bridge deck after panel installation and before UHPC placement.[25]



Source: FHWA.

Figure 27. Photo. Mixing operation for the field-cast UHPC.[25]

Source: FHWA.

plastic and a plywood lid to facilitate appropriate curing of the cementitious composite.

After the UHPC had developed sufficient strength, the formwork was removed, and the entire surface of the bridge deck was ground and grooved. This operation allowed the creation of a consistent, uniform driving surface over the entirety of the bridge deck, approach slabs, and approach pavement. The grinding included removal of concrete from both the UHPC connections and the precast deck panels, which also included sacrificial concrete. Figure 29 shows a completed bridge deck with two of the lanes open to traffic.

Figure 28. Photo. Placing operation for the field-cast UHPC.[25]

Source: FHWA.

Figure 29. Photo. Bridge deck after grinding, grooving, and opening to traffic.[25]

Source: FHWA.

Case Study: Construction of Sollars Road Bridge, Washington Court House, OH

UHPC has been used successfully for the longitudinal connection of adjacent box beams as early as 2006 on multiple projects in the province of Ontario, Canada. The first project to use this method in the United States was Sollars Road Bridge over Lees Creek in Washington Court House, OH, constructed in 2014.

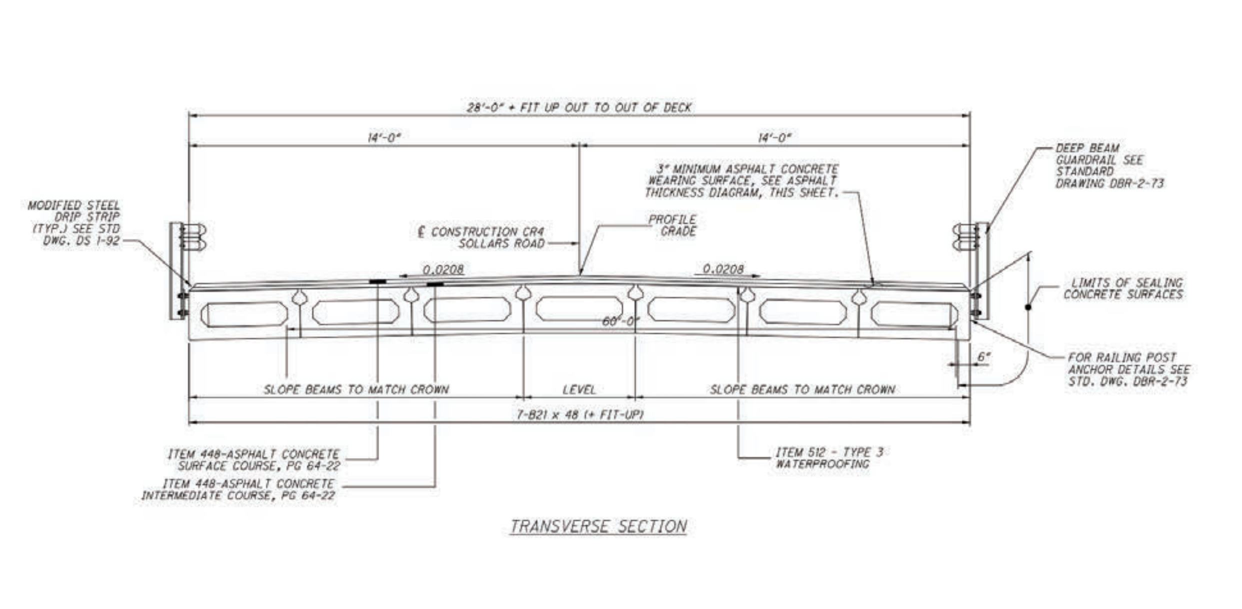
This single-span bridge carries two lanes and shoulders and has a span of 61 ft (18.6 m). The superstructure consists of seven adjacent precast prestressed concrete box beams (figure 30). Each box beam is 4 ft (1.2 m) wide and 21 inches (533 mm) deep with 7-inch (178-mm)-deep shear keys on each side. The bridge uses UHPC for the longitudinal connections between the box beams. Because of the use of UHPC for the connections, transverse post-tensioning was not used, and consequently, the boxes do not have intermediate diaphragms. The use of UHPC also eliminated the need for a cast-in-place slab. Thus, the box beams are topped only with a waterproofing membrane and an asphalt overlay.

After removal of the existing bridge and installation of the abutments, the adjacent box girders were installed by crane (figure 31 and figure 32) starting at the centerline, with each beam placed tightly against the previous one.

Figure 33 shows the connection detail in which adjacent box beams are butted together and the staggered reinforcing bars project into the connection. The surface of the box beams that will be in contact with the UHPC had an exposed aggregate finish to enhance bonding of the UHPC to the box beam.

The top plywood forms and chimneys were installed as shown in figure 34, and the longitudinal connections were ready for UHPC. The batching of UHPC was executed in two mixers at the far end of the bridge as seen in figure 34. Batching was completed in one mixer, while the contents of the other mixer were being discharged into wheelbarrows. Batching and discharging were alternated between mixers to provide a continuous supply of UHPC, filling each longitudinal connection completely before advancing to the next connection. The UHPC was transported from the mixers to the point of discharge by wheelbarrows. Connection filling started at the chimney at one end and continued successively through to the other end while maintaining a hydrostatic head in each chimney. Periodically

Figure 30. Illustration. Superstructure cross-section.



during the casting, the chimneys were checked and topped-up to ensure the hydrostatic heads were maintained as any entrapped air escaped during initial setting of the UHPC.

After the UHPC had developed sufficient strength, the formwork was removed and then a waterproofing membrane and asphalt wearing surface were installed.

Figure 31. Photo. First box beam in place, showing exposed rebar for longitudinal joint and wiring for instrumentation.

Figure 32. Photo. Setting the adjacent box girders.

Figure 33. Photo. Close-up view of a longitudinal connection between adjacent box beams.

Figure 34. Photo. Batching (mixers at far end of bridge), top forms, chimneys (orange buckets), and placing (filling through the orange buckets) of longitudinal connections between adjacent box beams.

Case Study: Rehabilitation of Franklin Avenue Bridge in Minneapolis, MN

Rapid Rehabilitation of a Mississippi River Crossing is a case study on the rehabilitation of the Franklin Avenue Bridge in Minneapolis, MN, using precast concrete deck panels with UHPC connections.(53) This document is available on the FHWA Every Day Counts website.(54)

Deployments

Between 2009 and 2018, nearly 200 bridge projects using field-cast UHPC connections between prefabricated elements have been completed in the United States.

Figure 35 and figure 36 show a map of all of the completed bridge construction or rehabilitation projects that include UHPC. Projects are shown in two groups, with projects completed before 2015 shown as white diamonds and projects from 2015 to 2018 shows as black circles. Many additional projects are under design or construction. The current version of this map can be accessed on FHWA's website.(4)

Figure 35. Map. Deployments of UHPC in bridges across the United States and Canada.

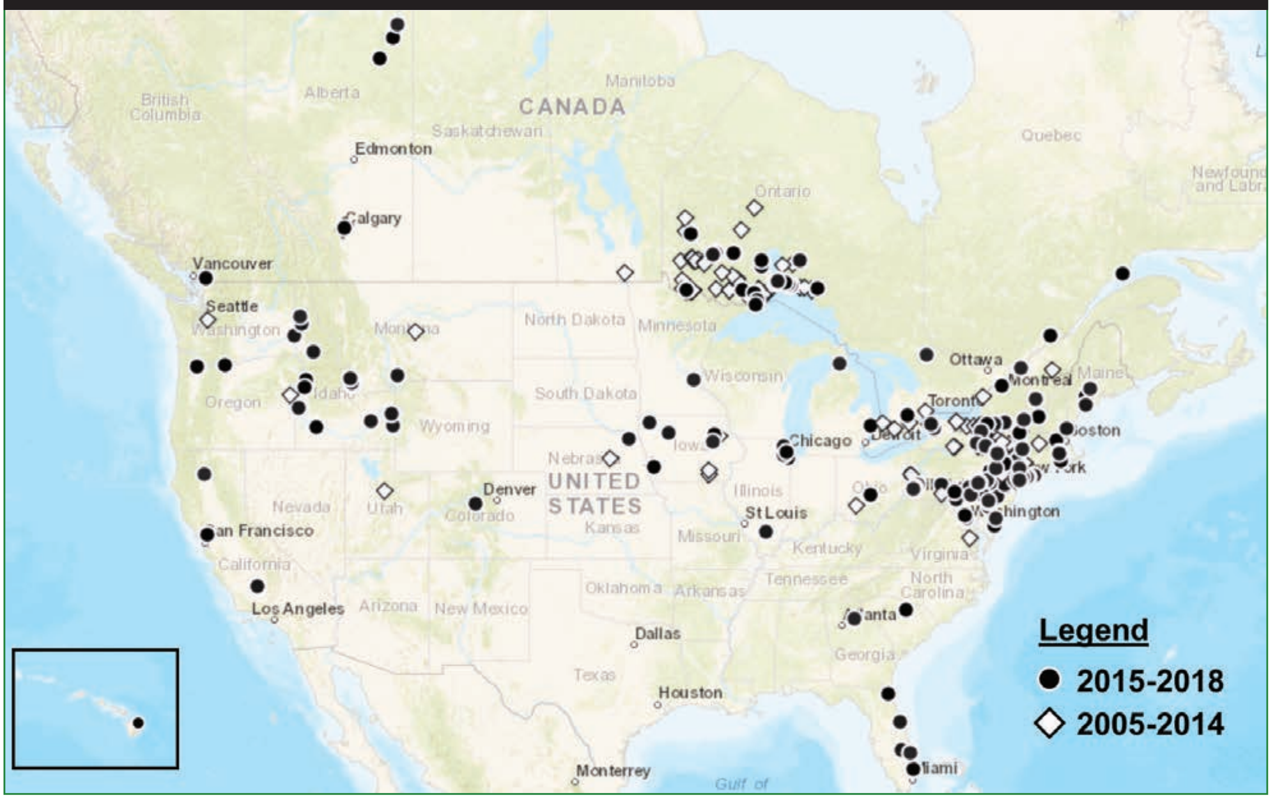
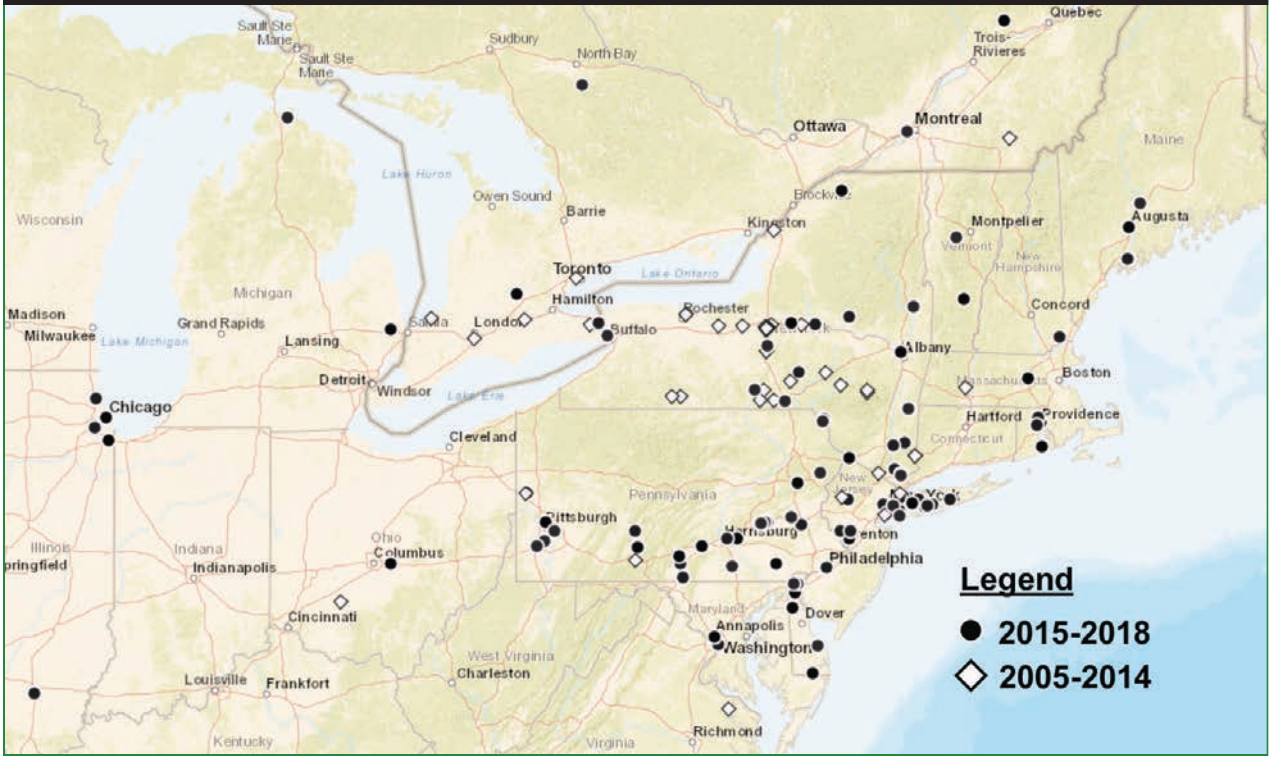


Figure 36. Map. Deployments of UHPC in bridges across the northeast United States.



Conclusion

Field-cast UHPC connections provide new opportunities to create robust structural systems composed of prefabricated components. The nearly 300 deployments to date in the highway bridge inventory have demonstrated the constructability and field performance of these systems. This document provides design and construction guidance relevant to field-cast UHPC connections. It is expected to facilitate broader deployment of PBEs by providing owners and contractors with the tools necessary to specify, design, and construct a new class of robust connection details.

Notation

d_b = nominal bar diameter.
E_c = modulus of elasticity of concrete.
f_c' = concrete compressive strength.
$f_{t,crack}$ = cracking tensile strength of concrete.
f_y = yield strength of reinforcing bars.
ℓ_d = development length.
ℓ_s = lap-splice length.

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Researchers—This document was developed by Ben Graybeal at FHWA's Turner-Fairbank Highway Research Center. Assistance was provided through contract no. GS00Q14OADU122 by Leidos, WSP USA, and V.iConsult. Additional information can be gained by contacting him at (202) 493-3122 or in the FHWA Office of Infrastructure Research and Development located at 6300 Georgetown Pike, McLean, VA 22101.

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Key Words—Ultra-high performance concrete, UHPC, fiber-reinforced concrete, bridge, accelerated construction, durable infrastructure, prefabricated bridge elements, design guidance, construction guidance, connection details.

FEBRUARY 2019

FHWA HRT 19 011

HRDI-40/02-19(1200)E