U.S. Department of Transportation
Federal Highway Administration

PROJECT CASE STUDY

REPLACEMENT OF BRIDGE 1-438 ON BLACKBIRD STATION ROAD

ULTRA-HIGH PERFORMANCE CONCRETE CONNECTIONS AND DECK OVERLAY

Introduction

In 2017, corrosion and soil instability were the leading reasons why Bridge 1-438 on Blackbird Station Road over Blackbird Creek (located near Townsend, Delaware) needed to be fully replaced. The Delaware Department of Transportation (DelDOT)—the owner and in-house designer for this project—wanted to use this bridge replacement as an opportunity to apply innovative accelerated bridge construction (ABC) techniques.

Bridge 1-438 was replaced with a structure consisting entirely of prefabricated elements, including precast adjacent box beams, abutments, wingwalls, and concrete piles, and prefabricated steel railing. As such, Bridge 1-438 became the first entirely precast bridge in Delaware. Bridge 1-438 also used ultra-high performance concrete (UHPC) longitudinal connections between the precast adjacent box beams (the second adjacent box beam bridge to do so in Delaware), UHPC end diaphragms, and a UHPC deck overlay (the second in the nation).

Figure 1 - Completed Bridge 1-438 on Blackbird Station Road © 2018 DelDOT

Project Background

The original Bridge 1-438 consisted of two 7-foot-high by 10-foot 8-inch-wide corrugated metal pipe arches (Figure 2). However, severe corrosion and loss of fill around the pipe arches required that the structure be fully replaced. The replacement of this structure provided an excellent opportunity for DelDOT to use innovative ABC methods in a relatively low-risk environment because the bridge is located in a rural area with a low average daily traffic and limited truck traffic. The goals for this project were to decrease onsite construction time, increase commuter and work zone safety, and minimize user costs through a decreased road closure time span. Additionally, this project provided DelDOT with valuable experience using UHPC as a connection material and deck overlay system.

The Choice of UHPC

Figure 2 – Original Bridge 1-438 on Blackbird Station Road © 2018 DelDOT

DelDOT chose to use UHPC for the adjacent box beam connections, the end diaphragms, and the deck overlay. UHPC's high strength, fast cure time, strong bond, extremely low porosity, discontinuous pore structure, and long-term durability make it superior to conventional concretes and grouts. These properties also make UHPC connections the strongest and most durable parts of a precast structure and enable UHPC deck overlays to effectively waterproof the entire underlying superstructure, thus protecting it from water and chloride intrusion.

In addition, UHPC's high compressive and tensile strengths (22,000 psi minimum in compression and about 1,000 psi in tension) allow it to fully develop reinforcing bars over very short distances, which leads to simple, narrow connections. Consequently, the amount of labor and materials necessary to construct the connections are minimized, resulting in significant time savings compared to traditional connection methods and materials. Time savings are further realized by UHPC's relatively fast cure time—typically only two to four days under ambient conditions.

The UHPC formulation used for precast connections is self-consolidating and highly flowable, which allows it to fill the narrow connections and to flow around reinforcing bars, thus eliminating most consolidation and air pocket problems. However, the UHPC formulation used for overlays is much thicker with thixotropic properties, which allows it to be placed on slopes as high as 6 percent or more without the need for top forming.

Approach to Replacement

At the beginning stages of the project design, DelDOT investigated several structure alternatives—including reinforced concrete pipes, precast box beams, a precast box culvert, and a precast rigid frame—but the existing hydraulic conditions of Blackbird Creek and the poor soils at the project location drove DelDOT's decision to use adjacent box beams. However, an early concern with the proposed structure was that many adjacent box beam bridges in Delaware had experienced reflective longitudinal cracking of the cast-in-place structural deck cast on top of the box beams and leaking through the joints between the box beams. Therefore, DelDOT decided not to follow its standard practice for box beam bridge connections and chose instead to use UHPC in a revised shear key detail that was developed and tested by the Federal Highway Administration. This new shear key design prevented joint leakage and changed the historically weakest part of any adjacent box beam bridge into the strongest part of Bridge 1-438. The high strength of the shear key also allowed DelDOT to eliminate the cast-in-place deck, which contributed to the overall construction time savings.

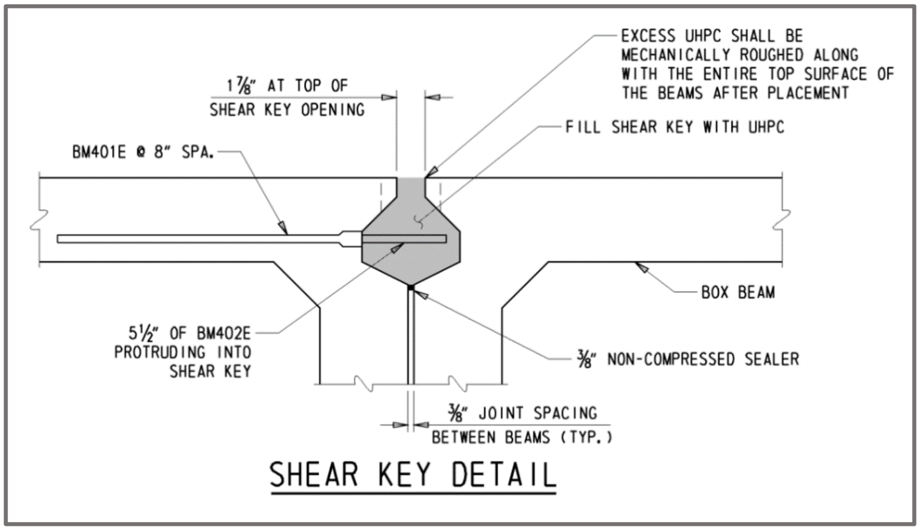

Figure 3 - Shear key detail. Rebar extending into shear key from right box beam not shown for clarity. © 2018 DelDOT

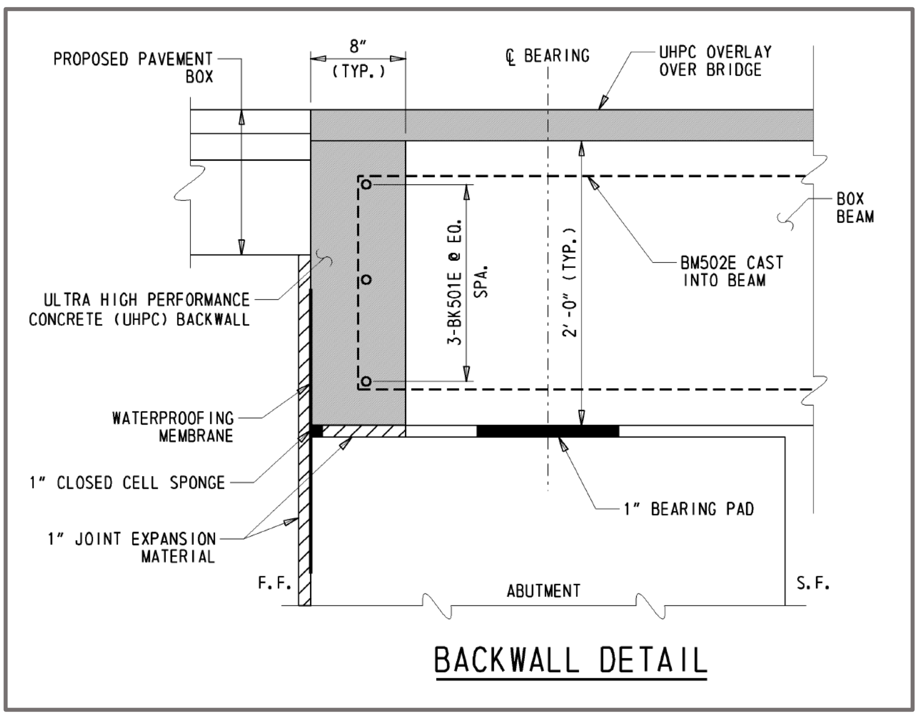

Figure 4 – UHPC end diaphragm (backwall) detail © 2018 DelDOT

DelDOT decided to use UHPC as a connection material between the box beams for two primary reasons: to prevent longitudinal reflective cracking and to expedite construction. The UHPC connections have proved to be durable; no longitudinal reflective cracking has been seen in Bridge 1-438 one year after construction. The UHPC shear key detail (Figure 3) was so effective that DelDOT has now adopted it as standard practice for adjacent box beam connections.

UHPC was also used for 8-inch-wide end diaphragms cast onto the ends of the box beams (Figure 4). The end diaphragms provided a full-depth connection between all the box beams. The UHPC protects the box beam ends from any moisture that might make its way through backfill and waterproofing membrane or through the approach pavement section. Also, in conjunction with the UHPC overlay, the UHPC end diaphragms protect the ends of the box beams from any hits by snow plow blades.

Because a full cast-in-place deck was not required, DelDOT decided to place a UHPC deck overlay to achieve the final bridge profile. This not only provided a faster cure time compared to a traditional cast-in-place concrete deck, but also boosted the long-term durability of the entire bridge. UHPC's properties allowed the overlay to be as thin as 1 inch, which minimized the amount of material superimposed on the box beams compared to a full cast-in-place concrete deck.

As part of DelDOT's commitment to a compressed construction schedule, the proposed timeline for on-site construction of Bridge 1-438 was only 33 calendar days. On-site construction began on August 8, 2017 and was completed on September 8, 2017 (two days ahead of schedule), proving the effectiveness of using precast elements in conjunction with UHPC.

Structural Features

In addition to the decisions to precast all the major bridge elements and to use a UHPC overlay in lieu of a cast-in-place deck, several other key design choices further expedited the construction duration. Precast prestressed concrete piles were used due to the poor soil conditions at the site. Since DelDOT was confident in the subsurface conditions, test piles and the production piles were fabricated simultaneously, which saved weeks of time. Additionally, the 46-foot-long precast abutments were cast in two sections each. The abutments had 27-inch-diameter vertical openings so that the sections could be placed directly over the concrete piles. After the abutment sections were set in place, a Type 1 concrete with a 2% high early strength admixture was used to connect the two sections of each abutment to each other and to fill the vertical openings to quickly connect the piles to the abutments, which allowed the precast box beam sections to be placed on the abutments after just one day. Casting each abutment in two separate sections facilitated their transportation and placement over the concrete piles.

The precast box beams were 52 feet long, 2 feet deep, and 4 feet wide. The top surfaces of all the box beam sections were tined by the beam fabricator to save time preparing the surface for the deck overlay. The outer box beam sections were precast with curbs and anchor bolts to allow for quick field installation of the metal railing. To combat differential camber of the interior and exterior box beam caused by the additional weight of the curb and barrier, additional prestressed strands were cast into the exterior box beams. However, the exterior beams were stiffer than predicted, and the interior beams experienced unexpected additional camber. This resulted in a differential camber of approximately 1.25 inches, which was addressed during placement of the UHPC overlay.

Figure 5 – The bridge after setting box beams in place, showing precast abutment wall joint, unfilled box beam longitudinal UHPC shear keys, and box beam rebar to connect to UHPC end diaphragm © 2018 DelDOT

Specifications and Application

DelDOT used a performance specification for specifying UHPC and required a minimum 28-day compressive strength of 22 ksi for the box beam connections and end diaphragms. For the UHPC overlay, DelDOT worked with the Federal Highway Administration, Iowa Department of Transportation, Iowa State University, and the UHPC supplier to develop the first construction specification for a UHPC overlay. The specifications required the overlay to reach a minimum 28-day compressive strength of 14 ksi, with a minimum thickness of 1.5 inches. The specifications also precluded pumping the UHPC, which could raise the temperature of the mix beyond workable limits. As per the specification, diamond grinding of the overlay could not be performed until the UHPC overlay had reached 75 percent of the minimum 28-day compressive strength, and traffic could not use the bridge until the UHPC overlay had reached the same minimum compressive strength.

Since DelDOT and the contractor, Zack Excavating, Inc., had no prior experience with UHPC deck overlays, the contractor performed a trial placement off-site. This demonstration provided key insights into the mix properties and placement processes unique to UHPC deck overlays. To see how the material would react during the demonstration, the contractor deliberately did not apply a curing compound or cover the overlay with polyethylene after placement. Under these conditions, the UHPC began to show cracking within 15 to 30 minutes, which indicated that it was imperative to immediately treat and cover the UHPC deck overlay after placement to prevent moisture loss. Additionally, during the trial placement the first 2 to 3 feet of the overlay was extremely rough until the contractor increased the vibration of the vibratory screed, after which the deck was much smoother. Therefore, the trial placement of the UHPC overlay proved to be an extremely valuable exercise for determining best placement practices.

Because UHPC is a relatively fluid material, it will ooze out of formwork if not contained in all directions. The contractor elected to use mastic to seal the shear key joints and poured the UHPC using a trough (Figure 6). When the connections around the trough filled up with UHPC, top forms were installed, and the trough was moved to a new location. These methods were effective, and no UHPC was lost during the connection pours. Because of the profile grade, camber, and cross-slope, the connections were top formed. Top forming often traps air bubbles that work their way out of the fresh UHPC, so an overpour of approximately 0.25 inch was used to keep the air bubbles out of the structural section.

Once the UHPC in the box beam connections had reached a compressive strength of 14 ksi, the top surface needed to be adequately roughened before placing the overlay. Since the box beams had already been tined during fabrication, all that remained to be prepped were the UHPC connection surfaces. A grinding machine was used to remove the UHPC overpour (including air bubbles trapped in the overpour due to the necessary top forming), which also created a roughened surface for the UHPC overlay to adhere to.

Figure 6 - Placement of UHPC in longitudinal box beam connections © 2018 DelDOT

The UHPC overlay was placed in two stages, with a longitudinal connection between the two stages running down the center of the bridge, located directly over a UHPC box beam connection. Before the overly could be placed, however, some adjustments to the work plan were made to address the 1.25-inch differential camber. First, during the grinding of the UHPC overpour, the higher box beam edge at the longitudinal connections was milled to increase the width of the transitions between the high and the low box beams. In addition, because the differential camber increased the total amount of UHPC overlay required, DelDOT decided to reduce the minimum overlay thickness from 1.5 inches to 1 inch where necessary. To make this decision, DelDOT referred to several successful projects in Switzerland that used a 1-inch minimum UHPC overlay and considered the fact that the UHPC box beam connections were located beneath the areas of minimum overlay thickness. After reducing the minimum thickness, the final overlay thickness on Bridge 1-438 ranged from 1 inch to 3.25 inches.

Another issue during the overlay placement was that the initial batch of the first placement was much stiffer than what was encountered during the trial placement. The first 8 to 10 feet of the first placement were very rough, with the material tearing as it was spread, so it had to be patched once a more workable mix was achieved. The patch ranged from just 0.25 inch to 0.5 inch in thickness, so there were some concerns regarding the bond between the UHPC patch and the previously placed UHPC overlay. However, the patch material held up through the subsequent grinding of the surface and has not shown any deterioration in the year since the bridge has been open to traffic.

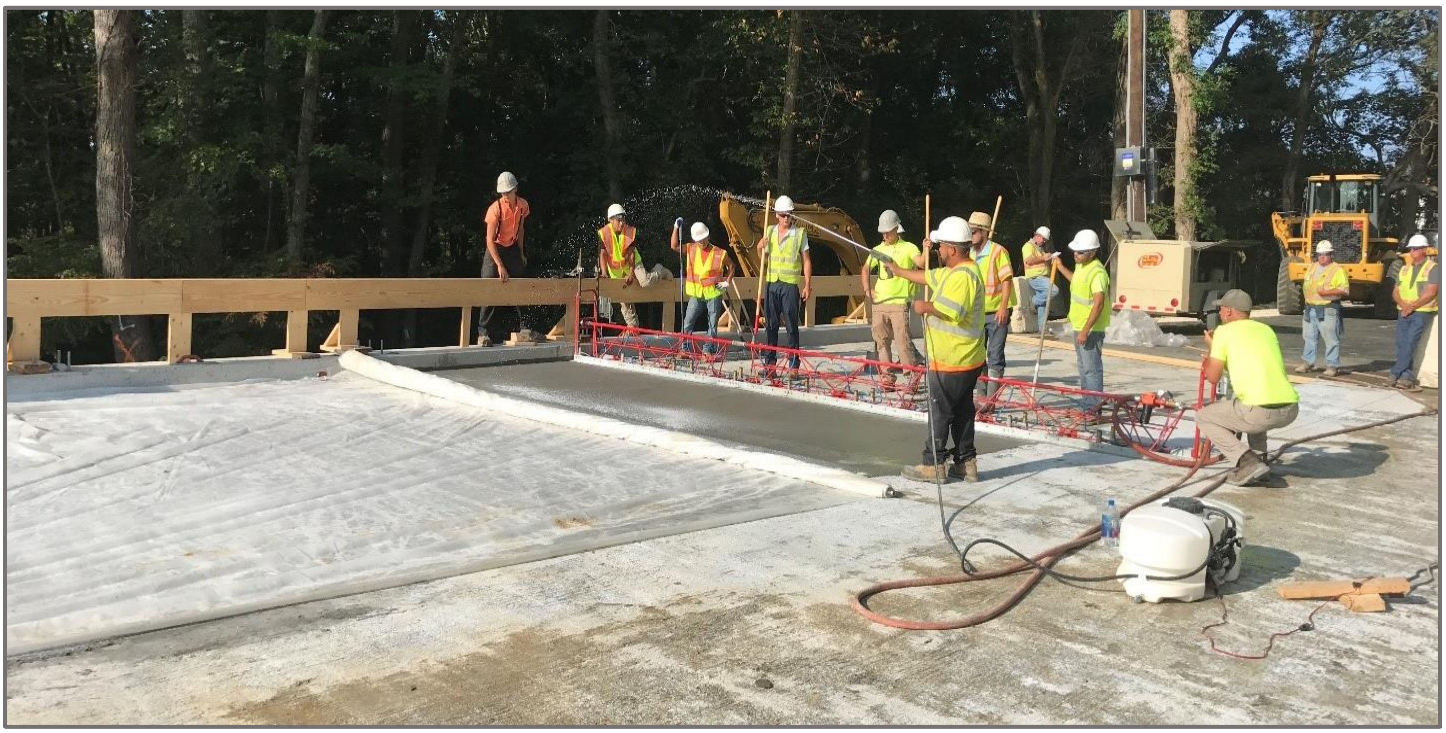

Figure 7 - UHPC deck overlay placement © 2018 DelDOT

A bonding compound was used at the longitudinal joint between the two UHPC overlay stages, without any other measures taken to ensure a watertight connection, such as stepping the joint or placing rebar in the overlay across the joint. This was because the overlay was as thin as 1 inch in some places along the joint, and because the consequences of any leaking would be minimal since the joint is located directly above a UHPC longitudinal box beam connection.

Figure 8 – Exposed steel fibers in UHPC deck overlay after grinding
© 2018 DelDOT

After both stages of the UHPC overlay reached 75 percent of the minimum 28-day compressive strength, a 4-foot grinder provided the final finish. The grinding process exposed the steel fibers of the UHPC deck overlay (Figure 8). Over time, these exposed fibers will completely deteriorate and be worn away by traffic. Although the final riding surface is not smooth to the touch due to the protruding fibers, it rides just as smooth as a cast-in-place concrete deck, and the UHPC deck overlay provides Bridge 1-438 with a more durable riding surface that is expected to be maintenance free for the next 100 years.

Summary

By combining precast elements with UHPC connections and a UHPC deck overlay, DelDOT expects the new Bridge 1-438 to provide a 100-year design life with minimal maintenance. Reducing on-site construction time and reducing future maintenance minimizes user costs and maximizes safety from construction through the service life of the bridge.

This project provided DelDOT with invaluable experience in using ABC methods in conjunction with UHPC. Although replacing Bridge 1-438 cost about one-third more than using traditional construction methods and materials, the project was completed in only one-third of the time. Therefore, DelDOT believes that using similar ABC methods on bridges with higher traffic volumes will save significant time over traditional construction methods. DelDOT also believes that the construction costs due to using ABC methods will continue to decrease as more standard details and specifications are developed and as contractors and designers gain more experience with these methods.

Although the cost of UHPC is higher than that of traditional overlay materials, UHPC's significant advantages offset the initial higher cost. For this project, the UHPC overlay's structural benefits were not considered, even though accounting for UHPC's high strength could permit the use of shallower members, which would further offset the cost of the UHPC and allow for creative alternatives at geometrically constrained locations. Additionally, UHPC deck overlays can be used to rehabilitate and extend the life of failing bridge decks.

Figure 9 - UHPC deck overlay final riding surface © 2018 DelDOT

Lessons Learned

- Communication between the designer, contractor, owner, and UHPC supplier is critical for achieving a quality product. Having the UHPC supplier on-site during UHPC placement can help to provide quick resolutions to any issues faced during construction.
- Demonstration pours are crucial for becoming familiar with the specific properties of UHPC, especially for contractors and designers who have limited experience with the material.
- A proper mix of UHPC should be ensured before placing the material. The patching of the first UHPC overlay placement could have been avoided by ensuring the mix properties were correct before beginning the initial placement. When the material becomes too stiff, it will not spread smoothly and may tear during placement.
- When using UHPC as an overlay system, the in-place material should immediately be treated with a curing compound and covered with polyethylene. If not immediately treated and covered, shrinkage cracks can form within minutes.
- Grinding a UHPC overlay system to the final riding surface exposes the steel fibers. The exposed fibers will eventually rust off. A UHPC overlay system may not be ideal for bridges with high pedestrian traffic or where pedestrians might be walking barefoot, since the exposed fibers result in a walking surface finish that is rougher, at least initially, than a traditional cast-in-place deck.
- For UHPC connections between precast box beams, it may be easier to use a chimney system rather than a trough system for controlling the pressure head of the connection pour. When using a chimney system, top forms are placed prior to pouring, and buckets are used to create a pressure head that forces the UHPC into all voids in the connection. For this project, the contractor noted that a chimney system would likely have been simpler, easier, and much faster.
- Mastic can be an effective alternative to spray foam for sealing connection interfaces prior to UHPC placement. For this project, the contractor used mastic to seal the shear key joints, and no UHPC was lost during the connection pours.

Additional Resources

- EDC-4: Ultra-High Performance Concrete Connections for Prefabricated Bridge Elements (UHPC) https://www.fhwa.dot.gov/innovation/everydaycounts/edc_4/uhpc.cfm
- TechNote: Design and Construction of Field-Cast UHPC Connections (FHWA-HRT-14-084) https://www.fhwa.dot.gov/publications/research/infrastructure/structures/14084/14084.pdf
- Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community (FHWA-HRT-13-060) https://www.fhwa.dot.gov/publications/research/infrastructure/structures/hpc/13060/13060.pdf

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