PROJECT CASE STUDY

REPLACEMENT OF HANGING ROCK CREEK BRIDGE

ULTRA-HIGH PERFORMANCE CONCRETE CONNECTIONS

Introduction

For many years the South Carolina Department of Transportation (SCDOT) has used hollow-core and solid-slab precast beams with conventional grouted keyways to replace bridges that experience low average daily traffic. This was because precast beams are very durable and accelerated bridge construction (ABC) methods could be used. However, the longitudinal shear keys of many of South Carolina's hollow-core and solid-slab precast beam bridges have deteriorated, resulting in reflective cracking in the bridge decks and wearing surfaces. This deterioration can be costly, because water can then travel through the cracks and corrode the beam's reinforcement and prestressing strands, resulting in expensive repairs and a shortened bridge life-span.

To combat this durability issue, SCDOT teamed with Clemson University to investigate more durable alternatives that could be constructed using ABC methods. It was determined through their research that the most viable alternative was to use northeast extreme tee (NEXT) D beams with ultra-high performance concrete (UHPC) connections. With the replacement of Hanging Rock Creek Bridge, SCDOT had the unique opportunity to test the durability of NEXT D beams with UHPC connections and compare them against hollow-core and solid-slab beams with UHPC shear keys. The design was performed in-house by the SCDOT Midlands Regional Design Office.

Project Background

Hanging Rock Creek Bridge (structure number 4160) is located on State Route S-770 (Shop Road) and spans Hanging Rock Creek, south of Kershaw. In 2016, Hanging Rock Creek Bridge needed to be replaced. This 220-foot-long, four-span bridge experiences relatively low average daily traffic, and therefore was a typical candidate for a replacement bridge that uses either hollow-core or solid-slab precast beams. SCDOT decided to replace Hanging Rock Creek Bridge with both hollow-core and solid-slab beams and also precast NEXT D beams. The hollow-core beams were used on the two center spans, and the solid-slab beams and the NEXT D beams were used on the end spans so that a direct comparison of the three beam types could be performed.

Figure 1 - Hanging Rock Creek Bridge during construction, with NEXT D beams in the foreground span © 2018 SCDOT

UHPC was used for the longitudinal connections on all four spans to eliminate deterioration of the connection material. Additionally, different longitudinal connection geometries were employed to compare their performance. Because all four spans were composed of precast beams, ABC methods could be employed. Replacement of Hanging Rock Creek Bridge began in late 2016, with the superstructure elements placed in March 2017 and the bridge reopened to traffic in July 2017.

The Choice of UHPC

SCDOT chose UHPC as the connection material for the longitudinal connections and shear keys because of its high strength, fast cure time, strong bond, and long-term durability. These unique properties make UHPC an ideal material for achieving durable accelerated bridge construction. UHPC is extremely durable due to its high strength, extremely low porosity, discontinuous pore structure, and embedded high-strength steel fibers. In terms of both strength and durability, these properties can make UHPC connections the strongest parts of a precast structure.

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. This leads to simple, narrow connections that fully splice reinforcing bars. For NEXT D beam connections, UHPC fully develops the transverse deck rebar that is exposed in the connection, resulting in a structurally continuous top slab across the full bridge width. This eliminates the need for longitudinal post-tensioning, which simplifies and accelerates construction. Time savings are further realized by the reduction of labor and materials necessary to construct the connections, as well as the relatively fast cure time of UHPC—typically only two to four days under ambient conditions.

UHPC is also self-consolidating and highly flowable, which allows it to fill narrow connections and flow around reinforcing bars, eliminating most consolidation and air pocket problems.

Approach to Replacement

The new four-span Hanging Rock Creek Bridge was designed to include three different superstructure types, each with a unique longitudinal connection. Span 1 is composed of 40-foot-long, 21-inch-deep modified NEXT D beams. Spans 2 and 3 are both supported by 70-foot-long, 24-inch-deep hollow-core beams, and Span 4 is composed of 40-foot-long, 21-inch-deep solid-slab beams with modified shear keys. In order to prevent shear key deterioration that SCDOT has witnessed on many hollow-core beam and solid-slab beam bridges in the past, UHPC was used for all longitudinal connections.

Due to its unique design, Hanging Rock Creek Bridge is an excellent case study for precast beams and longitudinal connections. Using three different types of precast beams and three different longitudinal connections for one bridge provides a unique opportunity for direct comparison of the long-term behavior of the beams and the connections. Additionally, Clemson University is monitoring the longitudinal connections for two years following construction, and SCDOT expects this program to yield invaluable information that can be applied to future bridge replacement projects that use precast beams.

Figure 2 - Interior modified NEXT D beam © 2018 SCDOT

Structural Features

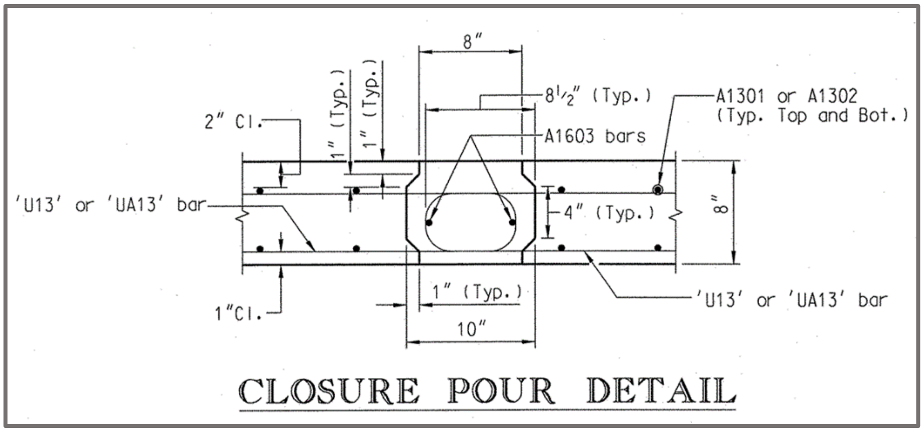

Figure 3 – NEXT D beam connection detail with minimum 8-inch joint opening © 2018 SCDOT

The Precast/Prestressed Concrete Institute Northeast developed the NEXT beam family, composed of the NEXT E, NEXT F, and NEXT D beams. The NEXT D beam is the only version with a fully integral precast deck. The configuration used for Hanging Rock Creek Bridge is a modified NEXT D beam that the SCDOT and Clemson University team modified (Figure 2). The smallest standard NEXT D beam is 28-inches deep with webs spaced at 5'-0", whereas the modified NEXT D beam has a depth of 21-inches and a web spacing of 3'-0". The connection shape and width were also slightly modified from the standard.

The NEXT D beam was selected as a viable alternative to hollow-core and solid-slab beams because it improves upon many of those beams' shortcomings. NEXT D beams do not have any voids like the hollow-core slabs, which reduces the risk of water infiltrating the beam and corroding reinforcement or prestressing strands. Additionally, NEXT D beams are easier to inspect, can accommodate utilities better, and connections are more easily poured. NEXT D beams have the same or similar structural depth as hollow-core and solid-slab beams for the same span length. NEXT D beams are also wider than hollow-core and solid-slab beams; therefore, fewer beams are needed per span, which results in quicker construction. For Hanging Rock Creek Bridge, only six NEXT D beams were required for Span 1, compared to 14 beams per span for the hollow-core and solid-slab beams in Spans 2, 3, and 4 (Figure 1).

The NEXT D beam connection is a full-depth joint (over the 8-inch-thick deck) with hairpin bars extending from each side (Figure 3). The minimum connection opening width used for Hanging Rock Creek Bridge is 8 inches, and UHPC fully develops and splices the reinforcing bars in the connection. The 8-inch-wide NEXT D beam connections allow UHPC to be easily placed, thereby reducing the probability of connection failure. Additionally, NEXT D beams have full-depth UHPC connections, which provide greater strength, durability, and resistance to reflective cracking. By contrast, the narrow shear keys for the hollow-core and solid-slab beams are more difficult to grout and do not allow for beam reinforcement to enter the connection. The lack of continuous reinforcement across the connection can contribute to shear key failure.

The UHPC fully develops and splices the NEXT D beam transverse deck-level rebar in the connection, and thus creates a structurally continuous top slab across the full width of the bridge. This eliminates the need for transverse post-tensioning of the NEXT D beams, which simplifies and accelerates construction.

The hollow-core beams in Spans 2 and 3 are precast, prestressed rectangular beams with circular voids located in the center of the beam and extending along the full length. To prevent deterioration of the shear key grout, the hollow-core shear keys were grouted with UHPC. The hollow-core connection is a 7-inch-deep partial-depth keyway with a very narrow top opening width of just 0.75 inch (Figures 4 and 5), which was more difficult to grout during construction. Because the hollow-core beam rebar did not extend into the shear key, transverse post-tensioning was applied across the full width of the bridge at the span quarter points to help keep the hollow-core beams in contact and share the load with each other.

Figure 4 - Interior hollow-core beams with minimum 0.75-inch shear key joint openings © 2018 SCDOT

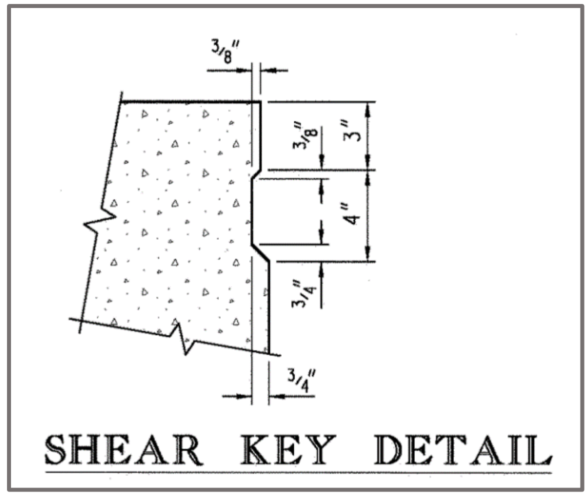

Figure 5 - Hollow-core beam shear key detail with minimum 0.75-inch joint opening © 2018 SCDOT

The solid-slab beams used for Span 4 are very similar to the hollow-core beams, except they do not have voids running throughout the length of the beam. Solid-slab beam bridges have experienced the same shear key deterioration as hollow-core beam bridges. The solid-slab beam shear keys were modified to be both deeper and wider than the hollow-core beam shear keys and those used on typical solid-slab beams, but were still not wide enough to extend the solid-slab beam rebar into them. While not completely full depth, the solid-slab beam shear keys extend 17 inches out of the total 21-inch beam depth. Additionally, the shear keys have a minimum top opening width of 2 inches (Figures 6 and 7), which is significantly wider than the minimum top opening width for the hollow-core beams, yet still much narrower than the NEXT D beam connection. Similar to the hollow-core beams, transverse post-tensioning was applied to help keep the solid-slab beams in contact with each other and to help provide some load sharing between the beams. The post-tensioning was applied at a 10-foot spacing, starting at 5 feet from the ends.

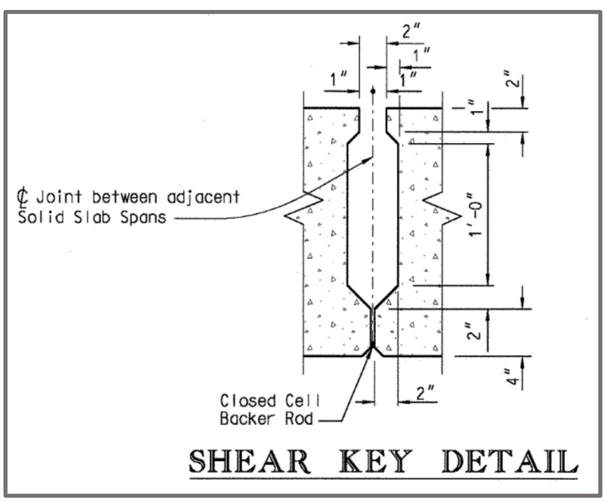

Figure 6 - Solid-slab beam shear key detail with minimum 2-inch joint opening © 2018 SCDOT

Specifications and Application

A UHPC performance specification with prequalification requirements was developed for Hanging Rock Creek Bridge. Because Clemson University had developed a non-proprietary UHPC mix, SCDOT informed bidders of the availability of the Clemson mix during a pre-bid meeting and allowed them to use any mix that met the performance requirements. The contractor (Dellinger, Inc.) elected to use a commercially available UHPC that met the performance requirements. Lacking prior experience with UHPC, the contractor believed working with a commercial supplier would reduce the risk of potential problems.

The prequalification testing was specified to validate the properties of the UHPC, and included testing for compressive strength, rapid chloride ion permeability, flexural strength, freeze-thaw resistance, drying shrinkage, autogenous shrinkage, alkali-silica reaction, pull-off bond strength, and reinforcing bar pull-out bond strength. The compressive strength was tested on 2-inch cubes of UHPC, and the test cubes had to attain 12 ksi compressive strength within three days and 21 ksi within 28 days to be acceptable for use on Hanging Rock Creek Bridge. The specification also considered the contractor's and SCDOT's limited experience with UHPC. An on-site meeting between the contractor and a UHPC product representative was required, and a UHPC product representative had to be on-site during all mixing and placement operations.

Figure 7 - Solid-slab beams with shear keys staged prior to construction © 2018 SCDOT

A reinforcing bar pull-out bond strength special provision was also developed for the project and was referenced in the qualification testing section of the UHPC specification. This special provision required tests of the pull-out bond strength for rebar cast into the UHPC to determine the appropriate embedment length. When applying a tensile force to the rebar, the test was deemed satisfactory if the failure occurred by yielding of the rebar instead of by pull-out of the rebar or fracture of the UHPC. This ensured that the UHPC would not be the weak link in the NEXT D beam span. This testing specification ensured that the UHPC material would result in a durable connection resistant to failure.

Figure 8 - Placement of UHPC in NEXT D beam connections using troughs © 2018 SCDOT

Figure 9 - Placement of UHPC, using chimney system and top formwork to control head pressure © 2018 SCDOT

During construction of Hanging Rock Creek Bridge, UHPC was placed using troughs (Figure 8). The formwork for the UHPC needed to be watertight, since the self-consolidating UHPC would flow out of any openings. The grade of the bridge also required top forms to prevent UHPC from flowing out of the lower end of a connection pour. Chimneys in the form of 5-gallon buckets with holes cut in the bottom were used to maintain head pressure to ensure that the UHPC completely filled the connections (Figure 9). Throughout construction, the contractor discovered that the wider joint opening made it easier to place the UHPC for the NEXT D beam connection pours.

The specifications required wet burlap to be placed over the connection areas within an hour after placement and kept saturated for a minimum of three days to prevent shrinkage cracking. However, on the advice of the UHPC material supplier, the burlap was not used, since the top forms were already required by the specifications to be left in place until the UHPC achieved a compressive strength of 12 ksi, and the top forms would prevent moisture loss. The UHPC typically reached 12 ksi compressive strength in two days, at which point the top forms were removed. The specifications called for the UHPC to be cast flush with the deck panels, so no grinding was necessary after top form removal. After the top forms were removed, a waterproofing membrane was placed on top of the concrete beams with an asphalt overlay to provide cross-slope and act as a wearing surface.

Unfortunately, the project specifications did not include any requirement to roughen the precast concrete surfaces in the connections or to ensure they were in a saturated surface dry condition prior to pouring the UHPC. As a result, the connection surfaces were smooth (Figure 10), although they were sprayed with water on the advice of the UHPC supplier to prevent the dry precast from pulling moisture out of the UHPC, which could degrade its mechanical properties and bond strength. The bond between the UHPC and smooth precast concrete is not as strong as the bond with roughened precast concrete with exposed aggregate. Smooth precast concrete surfaces in the connection create the potential for debonding, moisture penetration, and a shorter service life.

Figure 10 – NEXT D beam connection, note lack of surface roughening inside the connection © 2018 SCDOT

Monitoring Performance:

Clemson University is monitoring the multiple superstructure and longitudinal connection systems as part of a two-year monitoring program for Hanging Rock Creek Bridge. After the two-year monitoring period, Clemson University intends to publish a report comparing the performance of the systems and detailing the effectiveness of the various shear key details. The results of this program will provide useful information for the best design practices of shear keys for future precast bridge replacement projects.

Preliminary results from the Clemson University study show that one year after construction, there is no evidence of cracking or debonding in either the solid slab or NEXT D beam UHPC connections. However, the solid-slab beam UHPC connections were observed to experience much larger relative displacements than the NEXT D beam connections. This suggests that the post-tensioning rods in the solid-slab span may not be as effective as the NEXT D beam connections at limiting connection displacement and rotation due to live loads. It appears that distress is more likely to occur in the solid-slab beam connections than in the NEXT D beam connections.

Summary

Using ABC methods in conjunction with UHPC can result in a more durable bridge that can be constructed in a much shorter duration than a traditional cast-in-place bridge. ABC methods reduce construction time, resulting in fewer traffic delays and safer work zones for workers and commuters. Additionally, UHPC connections could significantly reduce bridge maintenance for up to 75 years or more. Reducing or eliminating deterioration of the longitudinal connections extends the service life of the entire bridge.

By using three different superstructure types—each with a different longitudinal connection detail—the replacement of Hanging Rock Creek Bridge is a unique opportunity for SCDOT to directly compare the long-term behavior of these systems as well as the relative performance of the three different longitudinal connection types using UHPC. Clemson University is continuing to monitor the performance of the three superstructure beam types and longitudinal connections. Although the results of this monitoring program are not yet available, SCDOT believes that the results will provide valuable information for determining best design practices for future projects utilizing precast beams.

Lessons Learned

- Based on early results of the Clemson University testing as well as prior industry experience, it is expected that using UHPC will result in more durable longitudinal connections, leading to significant long-term maintenance savings and an extended life-span for the bridge, and offsetting the higher initial cost of the material compared to traditional shear key grout.
- Exposing the precast beam transverse rebar in an 8-inch-wide longitudinal connection and pouring with UHPC allows the rebar to be full developed and spliced, making the rebar structurally continuous across the full bridge width and minimizing any differential deflection or separation of the precast beams. This eliminates the need for transverse post-tensioning that is normally used to prevent conventional shear keys from opening, thus simplifying and accelerating the bridge construction.
- Formwork for UHPC must be watertight. Fresh UHPC is a fluid material, and it will escape through any gaps.
- Before placement of UHPC, the interface surface needs to be roughened to expose the aggregate. Roughening the precast concrete connection surfaces is important to improve the bond of UHPC to the precast concrete in order to obtain watertight, durable connections.
- Pre-wetting the connection surfaces is important to obtain a good bond between the UHPC and the precast concrete. Without saturated surface dry conditions, the precast concrete can pull moisture out of the UHPC and degrade its mechanical properties and bond strength.
- Extra care should be taken to ensure that all reinforcing bars are properly placed in connections before UHPC is poured. UHPC is very difficult to remove after curing due to its high mechanical properties.
- The failure of shear keys can often be attributed to shear keys that are too narrow for proper connection material placement. Placement of UHPC is much easier in larger closure pours, and as such, wider closure pours are less susceptible to failure due to improper placement.
- Special provisions for the installation of UHPC ensure consistent and effective placement of the material.

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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