Performance Evaluation of Field Cast UHPC Connections for Precast Bridge Elements

Author(s) & Affiliation:

Peter J. Seibert, Trebona Consulting Inc., Vaughan, Ontario, Canada

Vic H. Perry, V.iConsult Inc., Calgary, Alberta, Canada

Dominique Corvez, LafargeHolcim, Chicago, Illinois, USA

Abstract:

For the past 20 years, Ultra-High Performance Concrete (UHPC) has been utilized in bridge construction across North America in various applications such as precast bridge elements, field cast connections, structural overlays, pier jacketing, repairs and seismic retrofit. Bridge owners are frequently faced with the need to replace structural elements of existing bridges and are asked to minimize traffic impacts to the general public during construction. UHPC, with its ultra-high strength, bond development and, durability, offers a great solution for use as field cast connections for precast bridge elements. This solution speeds up construction, allows for simpler connections with less reinforcing bar congestions and provides a longer lasting robust connections than other conventional methods. Over 250 bridges with UHPC field connections have been constructed in North America over the past 10 years.

This paper presents the historical evolution of UHPC in North American bridges and specifically a performance evaluation of field cast UHPC connections for selected bridge structures in New York State. The fundamentals of the technology, materials properties, design details, project profiles, and observed performance are included. The paper will assess the field cast UHPC connections to validate their long-term performance.

Keywords: UHPC, strength, durability, ductility, connections, precast

1. Introduction

UHPC facilitates the ability to design and construct better and longer lasting bridge structures with reduced user inconvenience during bridge construction/rehabilitation and with reduced maintenance costs during the life of the bridge structure.

One of the greatest challenges for bridge engineers is providing long-term durability and resiliency of bridge decks that continuously receive impact loading from trucks and that are exposed to other challenging environmental conditions. Years of continuous flexural and thermal stresses create long-term deterioration and maintenance issues (Bhide, S., 2008).

The use of precast High Performance Concrete (HPC) deck panels is a common method to speed construction and alleviate user inconvenience during initial construction; however connecting the precast system is a source for premature failure, leakage, and potential maintenance. Utilizing field cast UHPC can significantly extend the usage life of critical bridge structures, reduce the maintenance requirements, speed up construction cycle, and minimize inconvenience during construction.

An overview of the field cast UHPC technology and a historical evolution of UHPC in North American bridges will be discussed. The focus of this paper is to present the profiles and results of a visual inspection of selected highway bridges with field cast UHPC connections in New York State where systems have been in use over the past decade.

2. The UHPC Technology

"Ultra-High Performance Concrete (UHPC) is a cementitious, concrete material that has a minimum specified compressive strength of 150 MPa (22,000 psi) with specified durability, tensile ductility, and toughness requirements; fibers are generally included to achieve specified requirements" (ACI 239 Committee, 2018). Some jurisdictions (Canada & Switzerland) specify a minimum compressive strength of 120 MPa (18,000 psi) (Perry, 2018). The material matrix is typically manufactured from combining fine materials such as sand (< 400 microns), ground quartz, Portland cement, and silica fume. The matrix typically contains small fibers (12 mm x 0.2 mm diameter) in a very high dosage rate of 2% by volume. The matrix provides typical Chloride ion diffusion <0.02 x 10-12 m^2/s and it minimizes the ingress of chlorides or other aggressive agents. Durability properties are at least one order of magnitude better than most durable high performance concrete (Thomas et. al., 2012). Additionally, the total shrinkage is similar to grouts classified as non-shrink by ASTM (Graybeal, 2013). When compared to conventional or HPC concrete, UHPC is its own class of advanced cementitious material due to its higher compressive strength, tensile ductility bond development, and enhanced durability properties. These unique properties are a direct result of the low permeability pore structure and the addition of fibers. This excellent durability performance has been validated through long-term monitoring of UHPC samples exposed to a highly corrosive marine environment with annual freeze/thaw cycles since 1995 (Thomas et. al, 2012).

UHPC is a family of products with different formulations that are used for different applications such as highway bridges, pedestrian bridges, bridge overlays, field-cast connections and architectural facades. UHPC formulations vary in raw material ingredient dosages, fiber types and curing regimes and are now available from multiple suppliers. Testing the material properties and material characteristics of various UHPC classes and UHPC formulations from different commercially available suppliers indicated that all materials behave similarly with respect to some performance measures such as compressive strength, tensile strength, and durability, but vary with respect to others such as dimensional stability, bond to precast concrete, and compressive creep (Haber et al., 2018).

3. Historical Evolution of UHPC in North American Bridges

In North America for structural applications, UHPC was initially utilized to manufacture precast bridge elements in a controlled environment of a precast plant rather than using field cast UHPC. The first UHPC use in a bridge structure occurred in 1997, for the construction of the Sherbrooke Pedestrian Bridge (Figure 1), over the Magog River in Sherbrooke, Quebec, Canada (Blais & Couture, 1999). This 60 m (197'), clear span bridge was constructed from six precast 3-D space truss UHPC elements, post-tensioned together on site. Although not a highway bridge, it has been exposed to light vehicle loadings for snow removal, severe freeze/thaw in winters, as well as deicing salts for more than 20 years.

Figure 1. Sherbrooke Pedestrian Bridge

In 2006, the second pedestrian bridge was installed in Calgary, Alberta. The Glenmore/Legsby Pedestrian Overpass is a 53 m (174') single span bridge that stretches across 8 lanes of traffic and consists of two cantilevered, high performance concrete abutments and a drop-in "T-section" UHPC precast girder with an arch (Figure 2). The UHPC precast girder is 33.6 m (110') long, 1.1 m (3.6') deep at mid-span with a 3.6 m (12') wide deck and weighs approximately 100 tons. It was constructed with 13 mm (0.5") steel fibers and post-tensioned with 42 – 15 mm (0.6") strands. This girder required 40 m^3 (52 yd^3) of UHPC material, resulting in the largest, single monolithic UHPC pour at that time (Perry & Seibert, 2008).

Figure 2: Glenmore/Legsby Pedestrian Bridge

In 2001, the US Federal HighWay Administration (FHWA) initiated a research program to evaluate and introduce UHPC to the US Highway program (Graybeal, 2006a). Since the initiation of this program, significant progress has been made on validating the UHPC material technology (Russell & Graybeal, 2013) and in installing UHPC in US highway bridges. The FHWA has been instrumental in developing precast UHPC elements such as I-girders (Graybeal, 2006b), Pi-girders (Graybeal, 2009) and Waffle deck panels (Aaleti et. Al, 2013) as well as utilizing the material for field-cast connections between precast bridge elements. Other UHPC precast elements have been deployed as pier caps and pier column shells (Seibert et. al., 2013).

The first highway bridge in North America with a UHPC precast element was the Wapello County Mars Hill Bridge, Iowa in 2006 (Moore and Bierwagen. 2007). This 34 meter, single span, two-lane bridge has 3 – 34 m (49') long UHPC I-Girders (Figure 3) and a conventionally reinforced, cast-in-place concrete deck. This bridge is in the rural area of Iowa and is subject to very high "farm-to-market" loadings. The precast girders were manufactured without any stirrups for shear reinforcing. In 2008, a similar highway bridge (Cat Point Bridge) consisting with UHPC I-girders and a cast-in-place concrete deck was completed by the Virginia Department of Transportation.

Figure 3: Placing a UHPC I-Girder

During this same time, the FHWA was working on an "optimized" precast UHPC bridge profile, named the "Pi-Girder". After testing a prototype and reassessing the original Pi-girder shape, Buchanan County Iowa completed the Jakway Park Bridge using the 2nd generation, precast UHPC Pi-girder in 2008 (Figure 4).

The Wapello County, Iowa introduced a full-depth, precast UHPC Waffle deck panel with field cast UHPC connections with a fully exposed UHPC riding surface. The concept fully utilizes the true benefits of the technology. With a fully exposed UHPC deck, the surface should provide an extremely durable, long lasting and low maintenance bridge deck (Perry, et al. 2012).

Figure 4: Installation of 2nd Generation Pi-girder

4. Field Cast UHPC Connections for Precast Elements

While the FHWA and several US state DOTs were developing precast UHPC bridge elements, the Ministry of Transportation Ontario (MTO) was exploring the potential use of field cast UHPC connections between precast bridge elements. This need was created as the MTO had to rehabilitate and replace multiple existing bridge decks in remote rural areas along major highways. The bridges were often outside of the 1.5 hours delivery time range of ready-mix concrete plants making construction with high quality conventional cast-in-place concrete very difficult and costly.

The MTO recognized that conventional precast bridge components can provide high durability and good performance; however, conventional joints are often the weakest link in the system. UHPC offers superior technical characteristics including ductility, strength, bond development and durability while providing highly moldable products with a high quality surface aspect. Initial testing indicated that the bond development length of rebar in the UHPC connection can be very short due to the high compressive and tensile properties of UHPC which create a high bond stress. Later physical testing under static and cyclic loads confirmed that mild steel deformed reinforcing bars can be developed within approximately eight times the bar diameter, thus allowing for the lap splicing of straight bars within comparatively narrow connections (Graybeal, 2014). Since then shear connections that allow for a reduction or elimination of the interlacement of reinforcements emanating from mating components have also been developed and tested (ACI 239-R, 2018).

When used as a jointing material in conjunction with reinforced HPC panels, UHPC provides a synergistic approach for the reconstruction of bridge superstructures. The MTO also recognized that bridge replacements or major bridge rehabilitations could be completed in significantly less time (weeks vs months), thereby reducing driver inconvenience and related soft costs. Field cast UHPC connections for precast elements became the ideal solution for Accelerated Bridge Construction with the added benefit of a reduced maintenance costs throughout the life of the bridge structure.

In 2006, the MTO constructed the first bridge (Rainy Lake, ON) in North America using field cast UHPC connections for precast deck panels (Perry et al., 2007). This technology was used for shear pocket, transverse (Figure 5) and centerline panel connections (Perry & Seibert, 2013). To ensure continuous traffic flow, the bridge deck was replaced in two phases (Figure 6).

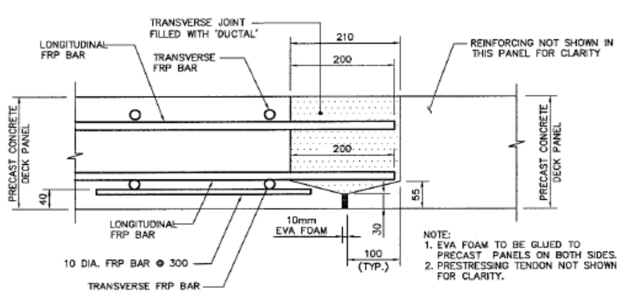

Figure 5. Transverse, full-depth precast panel joint

Figure 6. Rainy Lake Bridge Deck - Phase 2

In the USA, the first DOTs specifying, implementing and installing field cast UHPC connections were New York in 2009 (Perry and Royce, 2010), Iowa in 2011 (Aaleti, et al., 2013), Oregon in 2011 (Bornstedt and Shike, 2011) and Montana in 2012. Field cast UHPC connections have been used to connect bridge precast elements such as full depth precast deck panels, side-by-side box girders, side-by-side Deck Bulb-Tees, live-load continuity connections, precast approach slabs to abutments, curbs to decks, piles to abutments, columns to pier caps and in the haunches to provide horizontal shear for composite construction (Perry & Seibert, 2011). Field cast UHPC has also been utilized for pier repairs and retrofit projects across North America to enhance the structural and durability properties of an existing structure through jacketing, seismic retrofit, and encasement construction techniques (Doiron, 2016).

Since 2006, over 180 field cast UHPC projects have been deployed, with over 100 bridges in the USA by 20 DOTs and with over 80 bridges in Canada by 5 Provincial Ministries of Transportation (FHWA, 2019). Many projects have been described and reported in the literature.

5. Bridge Inspections

The main focus of this paper is to present the profiles and results of a visual inspection of selected highway bridges with field cast UHPC connections in New York State that have been constructed and in use over the past decade. In 2012, an initial field visit and visual condition survey was conducted on more than 40 bridge structures with field cast UHPC connections across Canada and the USA where the findings of six of these bridges were published (Perry, 2014).

In November 2018, a total of 20 New York State bridges with field cast UHPC connections were visited and visual inspections were performed. The weather conditions were cold, snowy and changeable between wet and dry for several days leading up to the field visits with temperatures around the freezing point. Even though these conditions seem not favorable for the inspectors, the continuous wetting of the bridge deck for several days provided favorable inspection conditions for leakage and crack detection. To our knowledge, the inspected bridges did not show any deteriorations related to field cast UHPC connections. Four of the inspected bridges, each with varying types of typical field cast UHPC connections are presented in the following sections.

5.1. Canandaigua Outlet Bridge, Village of Lyons, NY

The Canandaigua Outlet Bridge in the Village of Lyons, NY was the first use of Side-by-Side Deck Bulb-Tees with longitudinal field cast UHPC connections. This Accelerated Bridge Construction (ABC) project was completed within six weeks before the annual Village of Lyons Festival in 2009. The single span bridge consists of eight 26 meter (85') long deck bulb-tee girders, a waterproofing membrane and an asphalt wearing surface (Perry and Royce, 2010a).

A visual inspection of the deck surface (Figure 7) showed no evidence of any reflective cracking in the asphalt surface on top of the longitudinal field cast UHPC connections due to a potential differential movement of the girders; except the longitudinal centerline joint appeared to have a cold joint along the length of the bridge. This may be a result of having a crown along the centerline. The underside of the bridge was not accessible due to a high waterflow.

Figure 7. Deck surface with centerline longitudinal cold joint

This bridge has been in service for almost a decade now and other concrete deteriorations such as ASR cracking in the barrier walls, excess scaling of the sidewalk, rutting of the asphalt surface in the westbound lane, and failing of the eastside expansion joint were noticed (Figure 8). A crack from the failed expansion joint has also formed in the sidewalk. None of this deterioration was a result of using field cast UHPC connections.

Figure 8. Excess sidewalk scaling, expansion joint failure, ASR cracking and asphalt rutting

5.2. Otego Creek Bridge, Oneonta, NY

This single span project was the first full-depth precast HPC deck panels on five steel girders, with field cast UHPC connections by the New York State Department of Transportation. The bridge received a 50 mm (2") thin bonded HPC overlay. The field cast UHPC was only used in the 150 mm (6") wide full-depth panel-to-panel deck level connections in the transverse direction. The project was completed and put into service in 2009.

The visual deck surface inspection showed random plastic shrinkage cracking in the thin bonded overlay and wear & tear of the overlay grooving due to tire treads. There was no evidence of any reflective cracking in the thin bonded overlay over the UHPC panel-to-panel connections (Figure 9).

Figure 9. Deck Surface – No reflective cracking on top of panel-to-panel connection; wear & tear of grooving

There was a full depth (panel + overlay), full width transverse crack through the precast panel adjacent to each abutment, approximately the depth of the steel girders away from the abutment. Constructed with a semi-integral abutment, it is believed that this method provides enough rotational restraint so as to induce tensile cracking in the deck panels. A visual inspection of the underside confirmed evidence of efflorescence and leaking through the precast deck panel occurred at the full depth crack adjacent to each abutment. It can clearly be stated that no leakage occurred through the field cast UHPC connections as none of the galvanized channels originally used for forming the UHPC connections showed any signs of rust stains (Figure 10).

Figure 10. Underside Inspection - No leakage thorough UHPC connection; Full depth crack in precast panel

5.3. East Ridge Road, Rochester, NY

The East Ridge Road project consists of two bridges with 3 simply supported spans with a live load continuity joint across both piers of the center span. In 2013, a field cast UHPC link slab at the piers and a new waterproofing membrane with a 64 mm (2.5”) asphalt layer were applied to both structures (Figure 11). The flexural and durability properties of UHPC offer a great rehabilitation solution for a live load continuity link slab application.

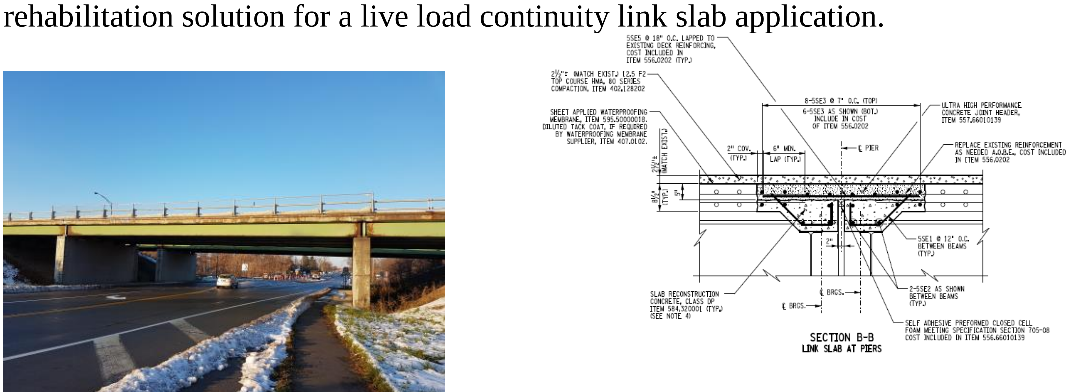

Figure 11. Installed Link slab at piers and design detail

The visual inspection of the deck surface showed no evidence of reflective cracking in the asphalt surface on top of the field cast UHPC link slabs of all piers (Figure 12). No leakage through the UHPC link slab was noticed. Only water draining down the side of the deck at the piers was seen causing surface rust staining of the steel fibers. The existing concrete deck experiences full depth cracking with leakage as well as the installed expansion joints at the abutments appear starting to fail (Figure 13).

Figure 12. No reflective cracking on top of UHPC link slab

Figure 13. Deterioration of existing bridge deck and expansion joint at abutment

5.4. Halstead Avenue, US Route 17, Owego, NY

This two-span simple supported bridge structure with 6 curved and sloped steel girders has a field cast UHPC live load continuity joint across the center pier and fully exposed deck-level UHPC connections between full-depth precast deck panels and approach slabs in the transverse direction. This bridge is the main artery to get from US Route 17 into Owego and was rehabilitated in 2013.

The precast deck panels revealed multiple random cracking beside, parallel and perpendicular to the UHPC connections throughout the entire structure (Figure 14). Only one UHPC connection showed a crack in the center line but no leakage was detected below the structure (Figure 15). This may have been caused by long spans providing flexible support and curvature resulting in centrifugal moment to be resisted in plane by precast deck panels. No cracking was detected above the live load continuity joint and no leakage below it was observed. All galvanized channels originally used for forming the UHPC connections showed no rust stains, therefore no leakage is evident.

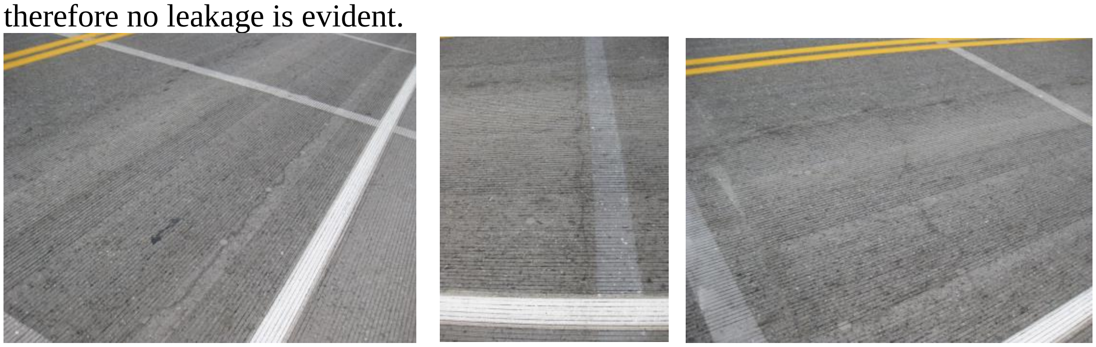

Figure 14. Multiple cracking longitudinal, beside and parallel to UHPC connections

Figure 15. Single crack in UHPC connection - No underside leakage – Bridge structure

6. Conclusions

Over 250 bridges with UHPC field connections have been constructed in North America since this solution was first introduced in 2006. The historical evolution of UHPC in North America illustrates how the original focus on precast UHPC elements has shifted to field cast UHPC connections for precast concrete elements.

This material shows very promising results for building better, more resilient, and longer-lasting infrastructure. Field cast UHPC and precast bridge deck systems can minimize traffic impacts and user costs through rapid construction while providing highly durable and sustainable bridge decks.

The presented projects are not necessarily a large sample size of projects, but the inspections presented do provide a level of comfort and added assurance for the completion of future UHPC bridge projects.

The bridge inspections showed that the field cast UHPC connections are either meeting or exceeding the design assumptions for the solutions. The absence of cracking, scaling, reflective cracking or other deterioration supports that the UHPC material is performing as expected by the designers. In comparison, other traditional concrete components of the bridge structure were observed to be deteriorating. The presented projects showed pavement scaling, ASR, asphalt rutting, overlay groove wearing, panel cracking, and expansion joint failing.

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