Application of Ultra High Performance Concrete in Expediting the Replacement and Rehabilitation of Highway Bridges

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Abstract

In Northwestern Ontario, the construction season is too narrow to complete the replacement and rehabilitation work of highway bridges using traditional cast-in-place concrete structural elements. In addition, the bridges built with cast in place concrete structural elements failed to exhibit durability. These cast-in-place concrete elements were disintegrating and severely scaled. To ensure long term durability and to accelerate construction of highway bridges, the Ontario Ministry of Transportation, in the Northwestern Region, started to incorporate precast prestressed concrete elements. The challenge in using these precast elements was to identify a reliable connection system to be installed among the precast elements. This paper presents examples of where Ultra High Performance Concrete (UHPC) was used for field cast longitudinal joints in precast prestressed adjacent concrete box girders and field cast joints and shear pockets in full depth precast deck panels. In addition, the details of a pier column shell and inverted T shaped pier cap built using UHPC are presented in this paper.

Keywords: Precast Prestressed Concrete, Ultra High Performance Concrete, Bridge, Accelerated Bridge Construction, Box Girder, Full Depth Deck Panel

1. Introduction

Since the mid-2000s the Ministry of Transportation (MTO) Northwestern Region has been actively researching, investigating, and implementing accelerated bridge construction (ABC) methods to decrease on-site construction duration and increase long term bridge durability. The bulk of the ABC implementation in Northwestern Region has involved the use of precast high performance concrete (HPC) bridge elements with Ultra High Performance Concrete (UHPC) field cast joints.

2. Background

The impetus for the introduction of precast elements and implementation of UHPC field cast joints in MTO Northwestern bridge projects was twofold: the quality of available ready-mix concrete and the numerous construction challenges related to bridge rehabilitations and replacements in Northwestern Ontario.

2.1 Concrete Quality

In the early 2000s, it was discovered that many regional bridge structures were experiencing premature deterioration of exposed cast-in-place concrete elements. In some cases, severe scaling and deterioration of cast-in-place concrete elements was occurring within the first year of service of the elements. After an investigation by the MTO, it was determined that the predominant causes for the premature deterioration included low concrete strength, segregation, poor bond between the cement paste and aggregate, non-conformance to some MTO specifications (substitution of materials, re-tempering of concrete, delivery time limits exceeded). The hardened concrete cores for testing were taken from favourable locations and not selected randomly. Analysis of the contract records revealed that the poor concrete was not specific to any individual batch plant or any specific aggregate source. Figure 1 shows premature concrete deterioration, which occurred within two years of construction, on the Thunder Creek Bridge located in Northwestern Ontario.

Figure 1. An Example of Premature Concrete Deterioration on an MTO NWR Project (Thunder Creek Bridge, MTO Site No. 41S-060)

2.2 Construction Challenges

In Northwestern Ontario, the MTO faces many challenges during highway bridge rehabilitation and replacement construction.

First, highway bridge structures in Northwestern Ontario are typically constructed across waterways and do not have nearby alternate routes, so bridge work is normally done in staged sequences, usually requiring traffic to be reduced to a single lane and controlled with temporary traffic signals.

Second, many Northwestern Region bridge structures are located in remote areas, hours away from urban centres; this limits access to some construction materials, such as commercial ready-mix concrete sources.

Third, the climate in Northwestern Ontario is such that it only permits a short construction season; typically, bridge construction is viable for only 5 to 6 months per year.

Fourth, a large portion of the existing Northwestern Ontario provincial bridge infrastructure, which was built in the 1950s and 1960s, is reaching the end of their service life, while at the same time the focus of recent Provincial spending has been on improving highway and bridge infrastructure; so the number of provincial bridge projects has dramatically increased which requires more bridge rehabilitations and replacements to occur simultaneously within the same restricted construction season.

The use of precast concrete elements enabled the MTO Northwestern Region to mitigate these construction challenges. The precast arrangement can be suited to allow flexible construction phasing for staged construction and precast elements can be fabricated in a plant and transported to remote locations to eliminate the need to transport ready mix concrete. To reduce on-site construction time, common practice for MTO Northwestern Region is to award contracts with precast components in the autumn to allow precast fabrication to occur over the winter and ensure that precast elements are ready for spring construction. With that reduced construction time, as well as other accelerated bridge construction techniques, more bridge construction projects are being successfully completed within one construction season to accommodate the increase in required bridge rehabilitations and replacements in Northwestern Ontario.

To further increase durability of precast components, the use of High Performance Concrete (HPC) was implemented. The MTO defines HPC as concrete with a minimum specified 28-day compressive strength of 50 MPa (7250 psi) and a Rapid Chloride Permeability (RCP) less than 1000 coulombs. This low porosity limits the intrusion of chlorides from de-icing chemicals. In addition, non-corrosive Glass Fibre Reinforced Polymer (GFRP) reinforcement bar was used as the primary reinforcement for precast concrete elements.

3.0 Ultra High Performance Concrete (UHPC)

The introduction of precast components into MTO bridge projects was only part of the solution. The precast elements needed a high strength, low permeability material that could connect them together. The MTO Northwestern Region determined that the best solution was UHPC for field cast joints and closure pours between precast concrete elements. Information on field-cast UHPC connections is available in literature (Graybeal)

The MTO defines UHPC as a concrete with a minimum specified 28-day compressive strength of 100 MPa (14500 psi) that is internally reinforced using high carbon steel fibres. For contract specification purposes, the MTO has developed a non-standard specification (NSSP), “Field Cast Joints for Precast Concrete Bridge Elements” for inclusion in MTO contracts which outlines design and submission, material, equipment, construction, quality assurance, and payment requirements for UHPC. For MTO bridges, Lafarge Ductal® was used as the UHPC material.

According to the NSSP, cementing materials must be in accordance with Ontario Provincial Standard Specification 1301 (OPSS, 1996) and Canadian Standards Association (CAN/CSA A3001, 2013), water must be in accordance with OPSS 1302 (OPSS, 1996), steel fibre reinforcement must be high carbon steel fibres with a minimum tensile strength of 2,500 MPa (360 ksi), 4-day minimum compressive strength must be 70 MPa (10150 psi), and 28-day minimum compressive strength must be 100 MPa (14500 psi). OPSS 1301 and OPSS 1302 prescribe the qualities of cementing materials and water, respectively. Plastic UHPC is tested for slump using a flow table test in accordance with American Society for Testing and Materials (ASTM C 109, 2012) on a flow table constructed according to (ASTM C 230, 2008) and must be within the spread range specified by the UHPC manufacturer. UHPC compressive strength, for the 4 and 28 day requirements, are tested using 75 mm (3 in) diameter 150 mm (6 in) long cylinders.

UHPC material is generally batched and mixed on site, under the supervision of a UHPC manufacturer representative. Common practice on the MTO projects is to cast the UHPC joints 6 mm higher than the finished surface. Later, the hardened elevated surface is ground down flush with the concrete surface using a mechanical grinder.

4. UHPC Applications in MTO Projects

Three categories of UHPC joints are presented below.

4.1 Longitudinal Joints for Box Girder Bridges

For bridges with spans between 10 and 40 metres (30 and 120 feet), MTO Northwestern Region will typically use adjacent precast prestressed concrete box girders as the superstructure type. Unlike traditional adjacent precast concrete box girders that typically require transverse post tensioning and a cast in place concrete distribution slab to distribute load between the adjacent girders, MTO Northwestern Region has been developing a precast prestressed concrete adjacent box girder system that is able to provide the required load transfer purely through the longitudinal field cast joint. This is possible primarily due to the use of UHPC as the field cast joint material. The UHPC can develop the full strength of the girder projection bars using only a short length of bar. In the case of the MTO box girder, the primary reinforcing material is GFRP bar with the projection bars typically being 15 mm (5/8 in) diameter. Figure 2 exhibits a typical MTO adjacent prestressed precast concrete box girder bridge deck section.

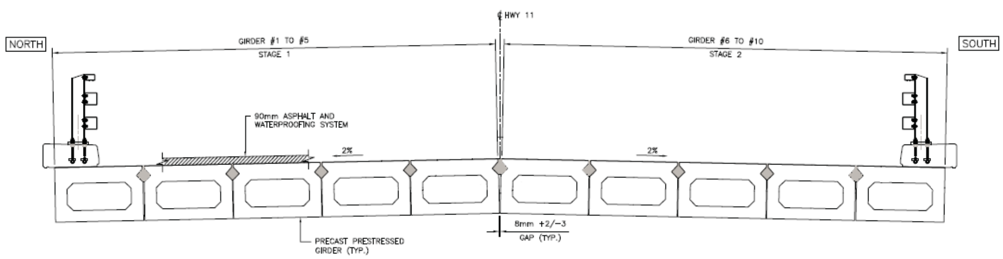

Figure 2. Typical MTO Adjacent Box Girder Bridge Deck Cross Section

Load distribution is achieved through the strength of the UHPC, the bond between the GFRP bar and UHPC, the strength of the GFRP bar, and the mechanical bond between the roughened keyway and the UHPC. The roughened surface is particularly important because the strength of the bond between the precast element and the UHPC can have a large impact on the capacity of the joint overall. For MTO projects, the specifications for precast concrete element fabrication will require a set retarder be applied to the formwork. The set retarder gets transferred to the concrete as it is placed and temporarily slows the concrete surface at that location from curing. The precast element is then pressure washed to remove the retarder residue and create the exposed aggregate finish. MTO specifications require a surface profile with minimum 4 mm (3/16 in) undulations. The embedment lengths of GFRP bars were chosen based on test results.

The keyway design has gone through a few iterations over the years reflecting the research outcome and field experience. The current design is a diamond shaped keyway with a 20 mm (3/4 in) gap at the top between the boxes. There are blockouts at various locations along the length of the joint to allow the UHPC material to be poured into the joint. Figure 3 shows a typical box girder longitudinal joint detail.

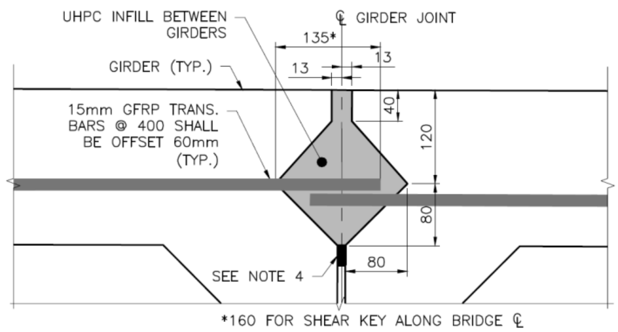

Figure 3. Typical Box Girder Longitudinal Joint Detail

The first structure of this type in Northwestern Ontario was constructed in 2008 and as of the end of the 2015 construction season, the Ministry of Transportation has constructed 42 adjacent box girder bridges with UHPC longitudinal field cast joints; 8 more are scheduled to be constructed during the 2016 construction season. Typically, for MTO Northwestern Region projects, a bridge deck will consist of 10 to 12 precast box girders, with girder widths ranging from 1100 to 1280 mm (44 to 51 inch), depths ranging from 600 to 1250mm (24 to 50 inch), and lengths ranging from approximately 10 to 38 metres (30 to 115 feet). Figure 4 shows the Black River Bridge comprised of adjacent prestressed concrete box girders located in Northwestern Ontario.

Figure 4. Adjacent Box Girder Bridge (Black River Bridge, MTO Site No. 48E-026)

There are several advantages to using this prestressed precast concrete adjacent box girder with UHPC longitudinal field cast joint design. First, this design includes primarily prefabricated components, which decreases on site construction time. Second, it provides a shallow superstructure, which is advantageous in complying with soffit elevation restrictions related to navigational clearance requirements. Third, this superstructure type can accommodate flexible construction staging, to allow a minimum of one active traffic lane to operate during construction. Fourth, this structure type has a high degree of durability when combining the UHPC joints with HPC elements and GFRP reinforcement; it is also common practice for the MTO to install hot applied waterproofing and asphalt pavement to the top of the bridge deck. In addition, this structure type can accommodate integral abutments to eliminate deck expansion joints and can accommodate simply supported or continuous superstructure articulations.

4.2 Connections and Joints for Precast Deck Panels

A common superstructure type in Northwestern Ontario for spans between 35 and 90 m (107 and 275 feet) is a steel plate girders and full depth precast concrete deck panels, with UHPC longitudinal and transverse joints and shear connections to create a composite connection between the girders and panels.

Using UHPC for the transverse and longitudinal panel joints allows the size of the connection to be reduced significantly to a typical width of approximately 200 to 250 mm (8 to 10 inches). The joint detail normally used includes a concrete lip formed as part of the panel, at the bottom of the joint, which acts as the bottom form for the UHPC and eliminates the need for formwork to be installed. The top of the joint is formed using either steel or wood formwork (Figure 5). The GFRP bars were used to avoid corrosion. In addition, GFRP bars are cheaper than stainless steel.

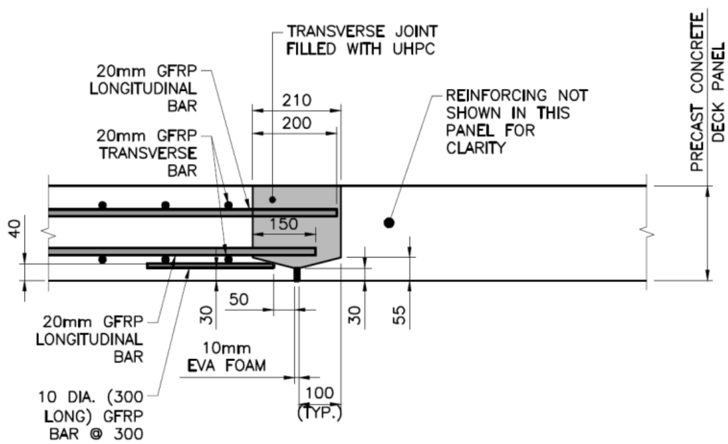

Figure 5. Typical Precast Deck Panel Joint Detail

For the girder to panel composite connection, this is achieved using either a distributed shear stud arrangement or a grouped stud arrangement. The panels are commonly placed on a set of temporary steel setting angles, welded to the girder top flange and sealed to the underside of the panel, to create the haunch (Figure 6).

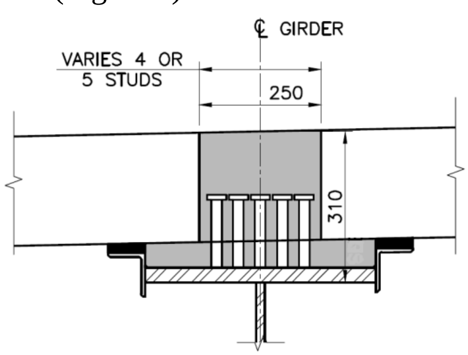

Figure 6. Typical Composite Connection Detail

Similar to the joints for the precast box girders, the face of the joint in the panels against which the UHPC is placed has the exposed aggregate finish, with undulations of at least 4mm, to provide a mechanical connection between the two materials. Also, similar to the box girders, the primary reinforcing is typically GFRP reinforcement and the type of concrete used is HPC.

4.3 Other UHPC Uses For Bridge Construction

In addition to using UHPC for constructing durable, strong field cast joints, the MTO Northwestern Region has also explored several other areas to use UHPC. For example, pier column shells were constructed using UHPC. These shells were fabricated in controlled conditions in a precast plant, transported to site, erected on the pier footing, and filled with concrete. These shells act as stay-in-place formwork and provide an impermeable jacket around the pier column concrete to protect it from chloride spray from adjacent traffic.

Another use for UHPC is in the construction of a high strength pier cap. The cap is an inverted T design which allows the pier cap to be recessed into the bridge deck, blending nearly seamlessly into the deck soffit. Figure 7 shows a bridge with pier column shells and a pier cap made of UHPC.

Figure 7. UHPC Pier Column Shells and Recessed UHPC Inverted T Pier Cap

In some bridge rehabilitation projects, new precast concrete deck panels were placed on the old concrete deck where the old deck and the new precast concrete deck panels were bonded by applying epoxy on top of the old deck panels before placing the new precast concrete panels. The joints among the precast concrete panels were comprised of UHPC.

MTO Northwestern Region has also used UHPC to increase the aesthetic value of normally plain looking concrete barrier end walls. The end wall panels were cast with a stone pattern using a common form liner, assembled into a box on site, and filled with concrete. The UHPC façade panels acted as stay in place formwork and provide a level of protection to the end wall for splash impacts of de-icing salts and chemicals.

Figure 8. UHPC Barrier Endwall Treatment

5.0 Construction Considerations

While UHPC is a strong, durable, and versatile material, there are some important aspects to consider during construction.

UHPC is very flowable and self-consolidating and typically does not contain any coarse aggregate. Therefore, all formwork must be constructed to a high tolerance and sealed to prevent any leakage of material. UHPC carries a premium cost and any small leak could add significant additional cost to the project.

The top formed surface of horizontal UHPC joints will often have small bug holes and will not have a uniform finish. It is common practice for MTO to require that the joint be poured 6 mm (1/4 inch) high and then ground down flush with the finished top surface height.

As mentioned previously, most of the MTO Northwestern Region bridge replacements are stage constructed. Typically, half of the existing structure is removed, with one lane of traffic operating on the other half, and the first stage of the new structure is built including the UHPC joints for that stage. Subsequently, traffic is shifted to the first half of the new structure, the remaining half of the existing structure is removed, and the new second half is constructed. Finally, the centreline UHPC joint between the two halves is placed to connect the deck. Since traffic is travelling on half of the structure while the centreline joint is being placed, it can have an effect on the quality of that joint. First, this traffic load can cause differential deflection between the two halves of the structure during the centreline joint placement and may result in the dowel bars moving up and down and creating slots in the UHPC material as it cures. This prevents a solid bond between the joint projection bars and the UHPC. Second, the live traffic will induce vibration in the deck which can cause the suspended steel fibres in the UHPC to segregate in the centreline joint material. To mitigate these issues, the MTO Northwestern Region details a temporary steel bracket that prevents differential movement between the two halves of the structure during the centreline joint pour. For further protection of the UHPC, traffic speeds are reduced to 10 km/hr (6 mph) on the structure during and 48 hours after the centreline joint pour, with a pilot vehicle. Figure 9 illustrates a typical temporary joint brace detail.

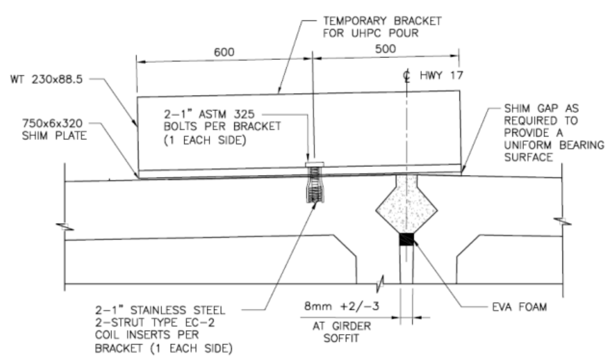

Figure 9. Temporary Centreline Joint Brace Detail

6.0 Conclusion

Ultra High Performance Concrete (UHPC) is a versatile material which has many uses in highway bridge construction and is an important component of the Ministry of Transportation of Ontario's accelerated bridge construction strategy. Applications for UHPC continue to increase and the MTO Northwestern Region prides itself on being a leading jurisdiction in its use. The use of UHPC assisted in completing staged construction of bridges in one construction season and eliminated the need for on-site and off-site detours, thus, reduced construction cost as well.

7. References

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