BEHAVIOR OF ULTRA-HIGH PERFORMANCE CONCRETE CONNECTIONS BETWEEN PRECAST BRIDGE DECK ELEMENTS

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ABSTRACT

The Federal Highway Administration's ongoing research program into the use of Ultra-High Performance Concrete (UHPC) in highway bridges has recently begun focusing on deck-level connections between modular precast components. In conjunction with the New York State DOT, researchers at the Turner-Fairbank Highway Research Center are investigating whether the exceptional durability, high strengths, and superior bonding characteristics of UHPC led themselves to the development of a new generation of connection details applicable to modular bridge components. A physical testing program has been initiated in which subassemblages of full-scale precast bridge deck panels are connected via UHPC closure pours then cycled under repeated truck wheel loadings. The test program has six specimens, with variables including joint orientation, slab thickness, reinforcement configuration, and reinforcement type. None of the specimens include any pre- or post-tensioning. Test results to date, along with two NYSDOT bridges constructed in 2009, demonstrate the potential viability of using UHPC as a closure pour material.

Keywords: Ultra-High Performance Concrete**,** UHPC, precast concrete bridge deck element, modular component, accelerated construction, closure pour, connection detail, high-cycle fatigue testing

INTRODUCTION

The Federal Highway Administration's ongoing research program into the use of Ultra-High Performance Concrete (UHPC) in highway bridges[1-8] has recently begun focusing on deck-level connections between modular precast components. In conjunction with the New York State DOT (NYSDOT), researchers at the Turner-Fairbank Highway Research Center (TFHRC) are investigating whether the exceptional durability, high strengths, and superior bonding characteristics of UHPC led themselves to the development of a new generation of connection details applicable to modular bridge components.

The U.S. highway transportation system is facing many challenges, not the least of which is increasing traffic volumes and aggressive climates stressing infrastructure that is nearing the end of its design life. One means of addressing some of these issues is through the reconstruction of bridges using modular components. The potential for increased safety and quality that comes from the use of prefabricated components is enticing; however, there is also the recognition that the use of these components frequently necessitates the use of field-cast connection details. Conventional construction practices for such connection details can result in reduced long-term connection performance as compared to the joined components. The implementation of UHPC as a closure pour material between precast components may facilitate: 1) simplification of the connection details, 2) overall enhancement of connection durability, and 3) a redesign of modular components whose details may be driven by connection-related considerations.

ULTRA HIGH PERFORMANCE CONCRETE

The term UHPC refers to a class of advanced cementitious materials. When implemented in precast construction, these concretes tend to exhibit properties including compressive strength above 150 MPa (21.7 ksi), sustained tensile strength through internal fiber reinforcement, and exceptional durability as compared to conventional concretes[1]. The specific UHPC investigated in this study is a product of a major worldwide construction materials manufacturer and supplier. It is currently the only product of this type that is widely available in the U.S. in the quantities necessary for large scale infrastructure applications. European and Asian markets currently have multiple suppliers, and a similar situation will likely occur in the U.S. as the market for this type of advanced cementitious product develops.

The composition of this UHPC includes four granular constituents. Fine sand, generally between 150 and 600 µm (0.006 and 0.024 inch), is the largest granular material. The next largest particle is cement with an average diameter of approximately 15 µm (0.0006 inch). Of similar size is the crushed quartz with an average diameter of 10 µm (0.0004 inch). The smallest particle, the silica fume, has a diameter small enough to fill the interstitial voids between the cement and the crushed quartz particles. Dimensionally, the largest constituent in the mix is the steel fiber reinforcement. In this study, the fibers in the mix had a diameter of 0.2 mm (0.008 inch), a length of 12.7 mm (0.5 inch), and a minimum tensile strength of

2,000 MPa (290 ksi). The fibers were included in the mix at two percent by volume. The typical mix composition of the UHPC used in this study, including the polycarboxylate-based superplasticizer, is provided in Table 1.

Table 1. Typical UHPC composition.

Material	Amount (kg/m^3 (lb/yd^3))	Percent by Weight
Portland Cement	712 (1,200)	28.5
Fine Sand	1,020 (1,720)	40.8
Silica Fume	231 (390)	9.3
Ground Quartz	211 (355)	8.4
Superplasticizer	30 (51)	1.2
Steel Fibers	156 (263)	6.2
Water	130 (218)	5.2

Prior research at FHWA investigated basic material properties of the UHPC engaged in the present study.(1) The properties of UHPC can vary depending on the curing methods applied to the concrete during the first weeks after casting. In particular, UHPC used in precast concrete elements is frequently steam treated resulting in significantly increased mechanical and durability properties. For the field-cast closure pour application discussed herein, it is likely that the UHPC would not receive any special curing treatments beyond normal conventional concrete curing practices. A brief summary of the relevant material properties for UHPC cured in this manner is presented in Table 2.

UHPC CLOSURE POUR CONNECTION

The vast majority of bridge decks are cast-in-place using conventional concrete construction practices. The widespread prevalence of precast concrete girder construction technology would seem to lend itself to prefabrication of bridge decks; however, a set of hurdles has slowed the implementation of this technology. Of particular relevance here, the connection technology currently available for modular bridge deck components is perceived to exhibit shortcomings that degrade long-term performance and/or increase initial project costs.

Many bridge owners in the U.S. have begun deploying precast bridge deck technology in order to gain experience with the potential benefits of this technology. Not unlike other owners, NYSDOT has experience with many varied technologies of this type and has a strong interest in facilitating further development in order to remove hurdles to future implementation. In particular NYSDOT is interested in full-depth precast deck panels and deck-bulb-Tee prestressed girders for use in constructing/reconstructing bridges. In both bridge types, the precast concrete elements must be connected together at the deck level via a permanent, durable connection. This connection is heavily stressed both structurally and environmentally, meaning that the long-term performance of the bridge is dependent on acceptable performance of the connection.

Table 2. Typical field-cast UHPC material properties.

Material Characteristic	Average Result
Density	2,480 kg/m^3 (155 lb/ft^3)
Compressive Strength (ASTM C39; 28-day strength)	126 MPa (18.3 ksi)
Modulus of Elasticity (ASTM C469; 28-day modulus)	42.7 GPa (6200 ksi)
Split Cylinder Cracking Strength (ASTM C496)	9.0 MPa (1.3 ksi)
Prism Flexure Cracking Strength (ASTM C1018; 305-mm (12-in.) span; corrected)	9.0 MPa (1.3 ksi)
Mortar Briquette Cracking Strength (AASHTO T132)	6.2 MPa (0.9 ksi)
Direct Tension Cracking Strength (Axial tensile load)	5.5–6.9 MPa (0.8–1.0 ksi)
Prism Flexural Tensile Toughness (ASTM C1018; 305-mm (12-in.) span)	$I_{30} = 48$
Long-Term Creep Coefficient (ASTM C512; 77 MPa (11.2 ksi) sustained load)	0.78
Long-Term Shrinkage (ASTM C157; initial reading after set)	555 microstrain
Total Shrinkage (Embedded vibrating wire gage)	790 microstrain
Coefficient of Thermal Expansion (AASHTO TP60–00)	14.7 $\times 10^{-6}$ mm/mm/ºC (8.2 $\times 10^{-6}$ in./in./ºF)
Chloride Ion Penetrability (ASTM C1202; 28-day test)	360 coulombs
Chloride Ion Permeability (AASHTO T259; 12.7-mm (0.5-in.) depth)	< 0.06 kg/m^3 (< 0.10 lb/yd^3)
Scaling Resistance (ASTM C672)	No Scaling
Abrasion Resistance (ASTM C944 2x weight; ground surface)	0.73 grams lost (0.026 oz. lost)
Freeze-Thaw Resistance (ASTM C666A; 600 cycles)	RDM = 112%
Alkali-Silica Reaction (ASTM C1260; tested for 28 days)	Innocuous

UHPC presents new opportunities for the design of modular component connections due to its exceptional durability, bonding performance, and strength. The properties of UHPC may make it possible to create small-width, full-depth closure pour connections between modular components. These connections may be significantly reduced in size as compared to conventional concrete construction practice, and could likely include greatly simplified reinforcement designs. Initial field deployments of this concept were completed in Ontario, Canada.(10)

Partners at NYSDOT developed a series of connections details for consideration and testing. These connections all include 152 mm (6 in.) wide female-female shear keys into which discrete reinforcement projects. The field-cast UHPC which fills the joint both develops the reinforcement within the joint and creates a cementitious bond between the precast and field-cast concretes. No prestressing or post-tensioning is included in the connections.

EXPERIMENTAL PROGRAM

A physical testing program has been initiated to assess the performance of UHPC closure pour connections. The testing focuses on the structural performance of each connection when subjected to cyclic and monotonic truck wheel loading. The testing is being completed on subassemblages of full-scale component connections in the Structural Testing Laboratory at TFHRC.

The connection details developed by NYSDOT were used to develop the test specimens. Details of the six test specimens are provided in Table 3. Four of the specimens simulate transverse connections between full-depth deck panels, while two of the specimens simulate longitudinal connections between the top flanges of deck-bulb-Tee girders. The six specimens were fabricated at the Fort Miller Company, Inc. in Schuylerville, New York.

Each specimen consists of two conventional concrete precast panels connected together by a UHPC closure pour. Figure 1 provides an oblique view of the top and side of specimen G1-G2. The concrete panels were cast first with the joint reinforcement extending through the shear key faces. The panels used a 35 MPa (5 ksi) design strength conventional concrete mix with approximately 45 MPa (6.5 ksi) 28-day compressive strength results. The UHPC was mixed by the precaster, cast into the joint between the two respective panels, and allowed to cure in the ambient environment. The 28-day compressive strength of the field-cured UHPC was 167 MPa (24.2 ksi).

There are two phases to the planned structural testing of each specimen. First, each specimen is cyclically loaded to simulate the fatigue performance of the joint under repeated truck wheel loading. Figure 2 shows the two test setups, one for each thickness of specimen. A 250 x 500-mm (10 x 20 inch) elastomeric pad backed by a 25-mm (1-inch) thick steel plate is used to apply a vertical load to the top surface of the panel immediately adjacent to the joint. The supports simulate the adjacent lines of girders which support a deck element in a bridge. The setup on the left in the figure simulates the wheel loading of a precast deck panel with transverse joints. The setup on the right in the figure simulates the wheel loading of the top flange of a deck-bulb-Tee girder.

Table 3. Test specimens.

Name	Orientation	Depth	Reinforcement
E1-E2	Transverse	200 mm	Alternating 13M (#4) hairpin epoxy-coated bars with 100 mm lap length and 55 mm spacing
G1-G2	Transverse	200 mm	Alternating 16M (#5) galvanized straight bars with 150 mm lap length and 450 mm (top) and 180 mm (bottom) spacings
B1-B2	Transverse	200 mm	Alternating 16M (#5) black straight bars with 150 mm lap length and 450 mm (top) and 180 mm (bottom) spacings
H1-H2	Transverse	200 mm	Alternating 16M (#5) headed black reinforcement with 90 mm lap length and 450 mm (top) and 180 mm (bottom) spacings
6B1-6B2	Longitudinal	150 mm	Alternating 16M (#5) black straight bars with 150 mm lap length and 450 mm (top) and 180 mm (bottom) spacings
6H1-6H2	Longitudinal	150 mm	Alternating 16M (#5) headed black reinforcement with 90 mm lap length and 450 mm (top) and 180 mm (bottom) spacings

1 in. = 25.4 mm

Figure 1. Photo of specimen G1-G2 in load frame during cyclic testing.

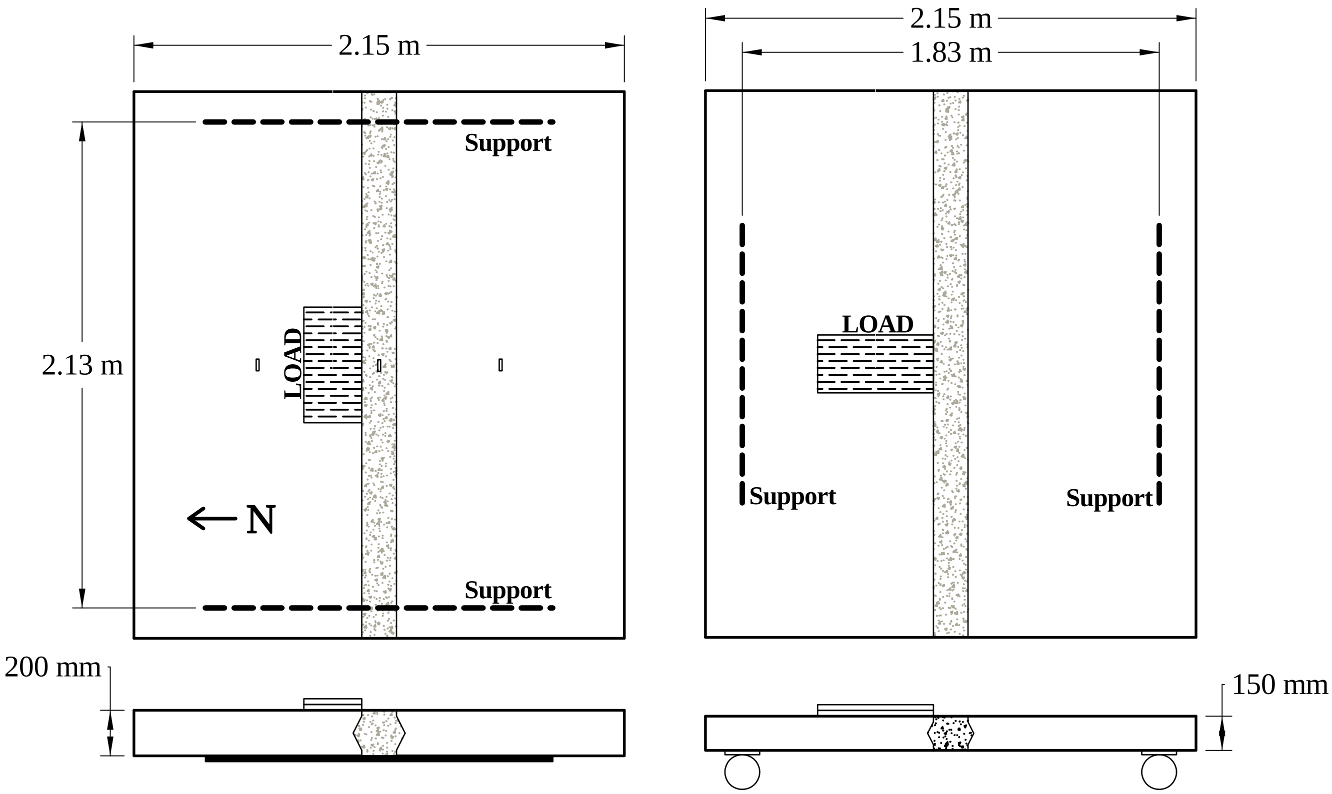

Figure 2. Test setup for cyclic loading including 200 mm (left) and 150 mm (right) specimens.

Cyclic loads are applied to each panel over a load range which generates a conservative estimation of the strain that a deck would undergo during service. An applied tensile strain of 100 microstrain is conservatively estimated as an upper limit for the strain that a service truck would impart onto a conventional concrete bridge deck. At this strain level, a conventional concrete deck would likely be approaching its tensile strength. Given the test setup implemented in this program, a peak applied load of 71 kN (16 kips) on the 200-mm (8-in.) thick deck generates this strain level under the load point.

Each specimen is monitored for damage during the cyclic testing. This monitoring includes visual assessment focusing on concrete cracking, electronic monitoring focusing on the flexural stiffness and strain distribution of the specimen, and leakage monitoring to assess interface debonding. If the specimen has not shown any degradation after at least 2 million cycles of loading, the upper limit on the load range is increased by a factor of 1.33. Cycling over this higher load range is then applied for at least 5 million additional cycles.

After the completion of the cyclic testing, the second phase of the testing of each specimen is initiated. Each specimen will be tested to failure though the application of a monotonically increasing load. The same loading and support locations shown in Figure 2 are used for this static testing. Each specimen is loaded to failure which is defined as increasing displacement occurring at decreasing applied loads.

TEST RESULTS

As of October 2009, the first phase of the structural testing has been completed on panels E1-E2, G1-G2, and B1-B2. The cyclic testing on the remaining three panels is anticipated to be completed by January 2010. The second phase of the structural testing will be completed thereafter, with final reporting anticipated in June 2010.

The performance of the specimens tested to date has met all benchmarks. Specifically, no deterioration in joint or overall specimen performance was observed during the cyclic loading to 71 kN (16 kips). Further cyclic loading to 95 kN (21.3 kips) resulted in tensile flexural cracking of each specimen. This cracking ran perpendicular to the joint across both precast panels and through the joint. There was no indication during the cyclic loading at either load level that the cementitious bond between the UHPC and the conventional concrete had failed anywhere along the joint. As such, the different reinforcement configurations in the joint were not significantly engaged and the potentially different structural performances thereof were not observed.

Figure 3 shows the strain and displacement results observed for specimen B1-B2 over the nearly 7.4 million cycles of structural loading that were completed. The lower portion of the figure shows the slope of the load strain response as captured during testing. These tensile and compressive strain results were captured along the centerline of the span via gages bonded to the surface of the specimen. The tensile strain results are not plotted after the increase in peak load level at 2.1 million cycles due to the cracking of the underlying concrete. The results demonstrate that the strain per applied load remains relatively constant during each phase of the cyclic loading. As such, it is clear that the load distribution across the joint through the cementitious bonds between the UHPC and conventional concrete is remaining intact. Similar behavior can be inferred from the upper plot in the figure as degradation of the joint would result in an increased hydraulic jack stroke range.

The tensile cracking response is also instructive. Figure 4 provides an illustration of the cracking response observed on the underside of specimen B1-B2 at the conclusion of the cyclic testing. This two-part figure shows both a strip along the midspan of the specimen from edge to edge, as well as a close-up view of the joint at midspan. All discrete cracks observed on the underside of the specimen are marked. The cracks in the precast panels, marked in red, were identified using the naked eye. Their width was measured to be approximately 75 μm (0.003 in.). The cracks in the UHPC closure pour, marked in cyan, were identified through the use of a volatile alcohol spray. These cracks were not optically identifiable with a hand-held crack microscope, thus indicating that their width was smaller than 13 μm (0.0005 in.). This type of cracking behavior wherein an individual discrete crack in the precast panel is replaced by multiple tight-width cracks in the UHPC has been observed in all three specimens tested to date. There has been no indication that any cracking or debonding has occurred at any of the joint interfaces in the three specimens tested to date.

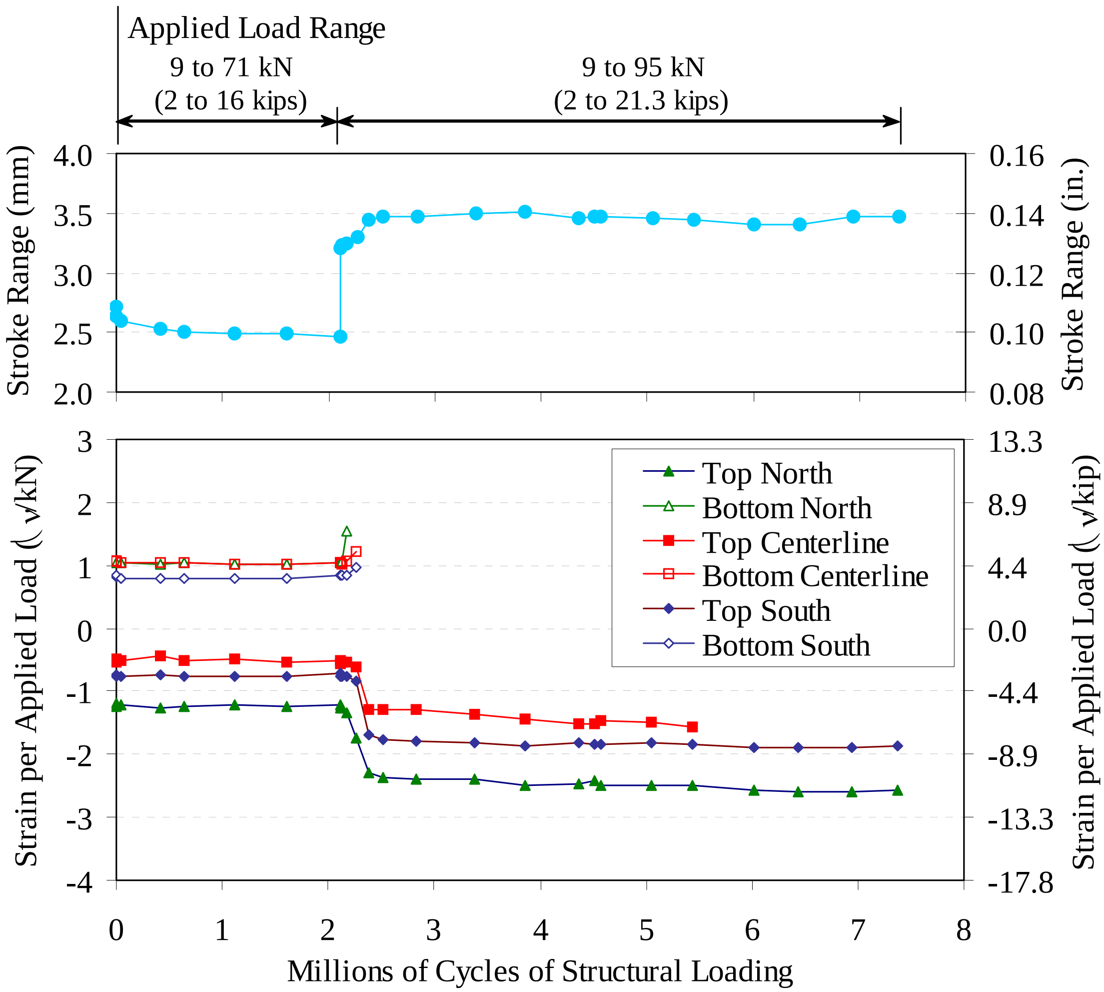

Figure 3. Cyclic test results for specimen B1-B2.

DEPLOYMENT EFFORTS

During the summer of 2009, NYSDOT completed two bridge projects using the UHPC closure pour concept. The first project was the Route 31 Bridge in Lyons, New York. In this bridge superstructure replacement, newly fabricated 1.04-m (41-in.) -deep prestressed concrete deck-bulb-Tee girders were installed in the bridge over the Canandaigua Outlet. In the bridge, the joint detail included epoxy-coated bars projecting from the precast girder decks into the closure pour joints. After adjusting the girder cambers and forming the joint, the UHPC joint fill was mixed and cast. After casting, the exposed surfaces were covered to prevent dehydration and the joint fill was then allowed to cure under the natural environmental conditions. After curing, the bridge deck surface was ground and a waterproof membrane and asphalt overlay were installed. A photograph of the UHPC joint casting is provided in Figure 5.

The second project was the replacement of the Route 23 Bridge in Oneonta, New York. This steel stringer integral abutment bridge spans the Otego Creek. The bridge deck construction included the use of precast deck panels and UHPC joint fill. The joint detail, which included galvanized bars, had geometry similar to that described as specimen E1-E2 in the structural testing program. After setting the precast panels on the girders and forming the joints, the UHPC joint fill was mixed and cast. After casting, exposed surfaces were covered to prevent dehydration and the joint fill was then allowed to cure under the natural environmental conditions. After curing, a 40 mm (1.6 in.) minimum thickness concrete overlay was installed so as to provide a smooth riding surface. Figure 6 shows the elevation view of this bridge.

The 505 m^2 (5436 ft^2) deck for the Route 23 Bridge cost NYSDOT \$657/m^2 (\$61/ft^2). Of this total, \$490/m^2 (\$45.50/ft^2) pertained to the precast panels and thin overlay, while the remaining \$167/m^2 (\$15.50/ft^2) pertained to the UHPC joints. For reference, the construction of the UHPC joints was bid on a per linear foot basis with the accepted bid costing NYSDOT \$500/m (\$153/ft). It is anticipated that the cost of future applications of UHPC joint fill will be reduced as contractors become familiar with the material and processes involved.

SUMMARY

The construction and reconstruction of highway bridges using modular components is an enticing concept whose implementation had been slowed by cost, durability, and constructability concerns. Much of the hesitancy can be linked to the design of the connections between components. Advanced cementitious composite materials such as UHPC present new opportunities to reconsider the use of modular components. UHPC when used as a closure pour joint fill can allow for simplified reinforcement configurations, smaller joints, better joint interface bonding, and better long-term durability.

NYSDOT is currently considering using UHPC as a closure pour material between prefabricated bridge deck components. NYSDOT is working jointly with FHWA to experimentally investigate the performance of UHPC bridge deck joints. A test program is ongoing at TFHRC wherein six deck panel subassemblages are being tested for fatigue resistance and ultimate capacity. These test specimens are being loaded by simulated truck loadings and are being monitored for joint degradation.

Results of three cyclic tests completed to date indicate that the UHPC joint fill can meet anticipated performance targets. No joint interface debonding was observed, and load distribution capability was maintained through the conclusion of cyclic testing. Also, the cracking behavior of the specimens demonstrates that individual structural tensile cracks in conventional concrete are interrupted and replaced by multiple tight-width cracks in UHPC.

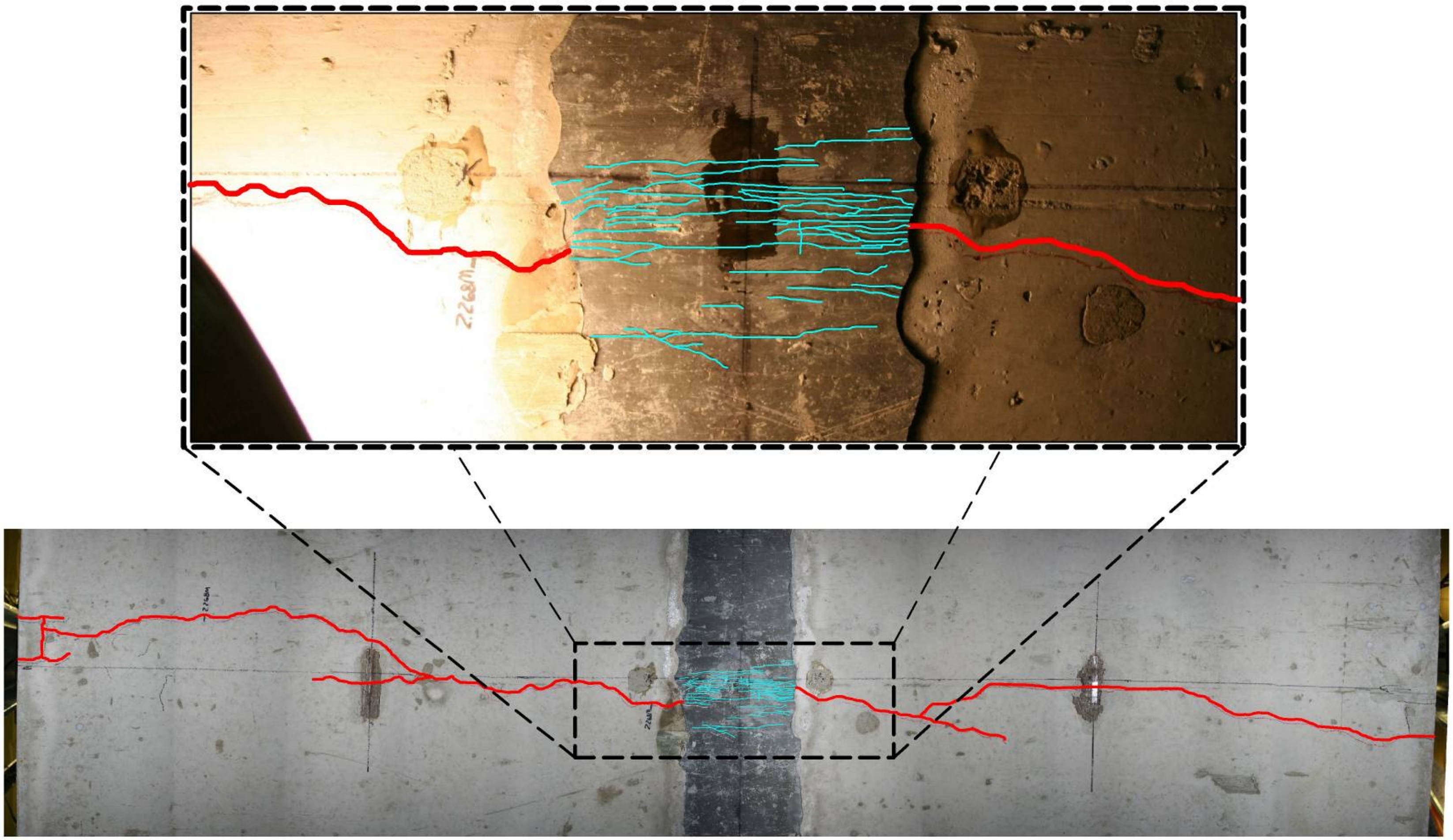

Figure 4. Cracking observed on underside of B1-B2.

Figure 5. Field-casting UHPC on the State Route 31 Bridge over the Canandiagua Outlet in Lyons, New York. *Photo courtesy of New York State DOT.*

Figure 6. State Route 23 over Otego Creek near Oneonta, New York.

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