CASE STUDY OF TWO ACCELERATED BRIDGE CONSTRUCTION PROJECTS IN THE U.S. USING PREFABRICATED BRIDGE ELEMENTS CONNECTED WITH UHPFRC

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Abstract

Accelerated bridge construction (ABC) techniques were used to rehabilitate two notable bridge structures in the United States in 2016; a 16.5-meter (54-foot) long single-span superstructure carrying U.S. Route 30 over Bessemer Avenue near Pittsburgh, Pennsylvania, and; a 5-span 308-meter (1,011-foot) long historic concrete arch bridge carrying Franklin Avenue over the Mississippi River near Minneapolis, Minnesota. These projects utilized prefabricated bridge elements (PBEs) that were connected together on-site using Ultra-High Performance Fiber-Reinforced Concrete ("UHPFRC"). Different UHPFRC mix designs, supplied by LafargeHolcim's Ductal®, were used for each project. A rapid-set mix used for the Pittsburgh project allowed the single-span superstructure to be replaced during a 57-hour weekend closure, while the Minneapolis project utilized a standard-set mix. In both cases, UHPFRC was used for its ability to rapidly achieve high strength as well as provide simple, strong, durable connections between the prefabricated elements.

Résumé

Les techniques de construction de ponts en accéléré (ABC) ont été utilisées pour réhabiliter deux structures remarquables de ponts aux Etats Unis en 2016 ; une longue superstructure à travée unique de 16,5 mètres portant la Route fédérale 30 au-dessus de l'avenue Bessemer près de Pittsburgh, Pennsylvanie, et un pont historique de 5 travées avec des arches en béton d'une longueur de 308 mètres portant l'avenue Franklin au-dessus du Mississippi près de Minneapolis, Minnesota. Ces deux projets ont utilisé des éléments de ponts préfabriqués qui ont été connectés en place entre eux en utilisant du béton fibré à ultra-hautes performances (BFUP). Différentes formulations de BFUP, fournis par Ductal®, ont été utilisées pour chaque projet. Une formule à prise rapide a été utilisée pour le projet de Pittsburgh qui a permis à la superstructure à travée unique d'être remplacée pendant que la route était fermée durant 57 heures, tandis que le projet de Minneapolis a utilisé une formule à prise normale. Dans les deux cas, le BFUP a été utilisé pour sa capacité à atteindre rapidement une résistance élevée et fournir des connections simples, résistantes et durables entre les éléments préfabriqués.

1. INTRODUCTION

The use of UHPFRC (commonly known as "UHPC" in North America) in bridge infrastructure projects in the United States has grown substantially over the past four years. From 2005 (the year the first UHPFRC bridge project in the U.S. was built) to 2012, only 20 bridges had been constructed using UHPFRC in some form [1]. Since then, more than 80 additional bridges have been constructed where UHPFRC was incorporated into the design [2]. The majority of these 100+ projects have used UHPFRC as the closure pour material between various types of prefabricated bridge elements (PBEs) in order to accelerate the on-site construction schedule, improve the long-term durability of the PBE system, and simplify the fabrication and erection procedures.

In 2016 alone, more than 30 of these 100+ bridge projects were completed using this PBE+UHPFRC approach. This paper will discuss two of these projects in more detail. The first project is the Franklin Avenue Bridge over the Mississippi River where UHPFRC was used as the closure pour material between precast concrete deck panels to rehabilitate the bridge deck. The second project is the U.S. Route 30 Bridge over Bessemer Avenue, where UHPFRC was used as the closure pour material between prefabricated steel beam modules to replace the existing deteriorated superstructure.

2. U.S. BRIDGE INFRASTRUCTURE

The American Society of Civil Engineers (ASCE) released an Infrastructure Report Card in 2017 rating various types of infrastructure throughout the U.S. [3]. According to that report, bridge infrastructure in the United States is rated a C+ (i.e. average/mediocre), primarily due to the old age and deteriorating conditions of the bridges in the network. The average age of the nation's existing bridges is 43 years and according to the U.S. Federal Highway Administration (FHWA), almost 40% have exceeded their intended 50-year service life. In fact, out of 614,387 bridges, 56,007 of these bridges are classified as structurally deficient. While this only amounts to approximately 9% of the nation's total number of bridges, they make up one-third of the total bridge decking area in the country, meaning that the bridges which are classified as structural deficient are significant in size and length.

Additionally, the bridges that need the most attention tend to be located in metropolitan areas where population density and traffic volumes are highest. This presents a significant challenge for the rehabilitation and replacement of these deficient bridges. Hence, many transportation agencies are now looking to Accelerated Bridge Construction (ABC) methods in order to expedite the on-site construction schedule and reduce user delays.

3. PREFABRICATED BRIDGE ELEMENTS & UHPFRC

One of the most popular ways of accelerating the on-site construction schedule is through the use of prefabricated bridge elements and systems (PBES). This methodology involves the fabrication of bridge elements off-site (or adjacent to the site) which are then shipped to the project location and assembled on-site. This type of system has been in use for several decades; however, the long-term performance of these assemblies has been unreliable over the years, primarily due to poor-quality materials being used in the connections of the assembly. Inferior materials such as non-shrink grout and conventional concrete have been used frequently, leading to premature cracking of the joints and subsequent leakage, corrosion, and deterioration of the entire system.

As an example, during the 1980's the Pennsylvania Department of Transportation was reconstructing bridge decks using precast concrete deck panels longitudinally post-tensioned together on-site with keyways between the panels filled with a conventional grout. After just 10 years of service, inspectors noticed that water was getting into the joints between the panels and deteriorating/corroding the keyway material and post-tensioning tendons causing the deck panels to move under traffic [4]. This is just one example of many where inferior joints led to premature failure of the PBE system.

More recent joint details have included the use of hairpin or headed rebar extending into the joint (see Fig. 1). This detail was adopted to reduce the development length of the rebar and subsequently reduce the joint widths. However, it has created challenges for precasters to fabricate because it makes forming of the panels more difficult, costly, and labor intensive. It has also led to conflicts during the erection and placement of these elements in the field. Lastly, conventional closure pour materials are still prone to shrinkage cracking and delamination from the precast elements leading once again to leaky joints and corroding reinforcing steel in the joint.

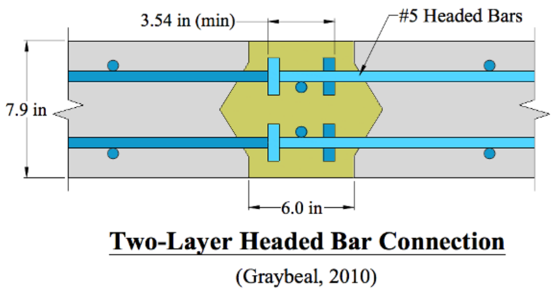

Figure 1: Conv. Joint with Headed Rebar

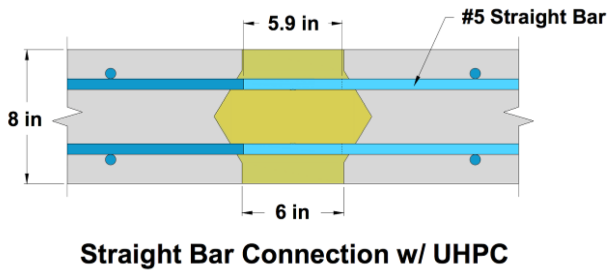

Figure 2: UHPC Joint with Straight Rebar

The use of UHPFRC as a closure pour material has significantly simplified the joint detailing (see Fig. 2) while drastically improving the long-term durability of the connection. This application has been extensively researched and investigated by FHWA since 2008. Consequently, the FHWA has also published numerous reports that validate UHPFRC's ability to create simple, strong, durable connections [5]. Some of these tests included rebar bond in UHPFRC [6], bond of UHPFRC to substrate materials [7], and full-scale mock-up assemblies of concrete elements connected with UHPFRC. The results have shown that straight rebar can fully develop in very short lengths; that bond to substrate materials can outperform the capacity of the substrate materials themselves with proper surface preparation and; that the prefabricated assemblies ultimately behave as monolithic-like sections.

Since replacement of deteriorated bridge decks is the most urgently needed type of structural rehabilitation and because prefabricated full-depth deck panels are the fastest form of deck replacement available, the FHWA has been encouraging the highway community and Departments of Transportation to use UHPFRC connections in their precast deck panel replacement projects and other PBE projects. They are doing this by promoting the technology via traveling educational workshops and remote webinars through their "Every Day Counts" (EDC) program that began in 2015. FHWA will continue to promote this application during its fourth round of the program, until the end of 2018.

4. PROJECT CASE STUDIES

4.1 Franklin Avenue Bridge over the Mississippi River

The Franklin Avenue Bridge (officially named the F.W. Cappelen Memorial Bridge), is a five-span, open-spandrel, concrete-deck arch bridge that carries Franklin Avenue over the Mississippi River in Minneapolis, Minnesota (see Fig. 3). The bridge is 308-meters (1,011-feet) in length and had the longest concrete arch span in the world at 122-meters (400-feet) when first constructed in 1923. As such, the bridge was listed on the U.S. National Register of Historic Places in 1978 and dedicated a Minneapolis landmark in 1985. The bridge is adjacent to the University of Minnesota and is an important structure for both vehicular and non-vehicular traffic serving more than 10,000 crossings per day.

Figure 3: Franklin Avenue Historic Arch Bridge

The bridge underwent substantial renovation in the 1970's which included the removal and replacement of the original deck and spandrel supports. However, decades of deterioration since then have taken its toll. A structural investigation in 2007 showed that the bridge was structurally sound, but needed additional rehabilitation due to significant deterioration that had occurred in the deck and supporting members, primarily due to leakage at the deck expansion joints. The owner, Hennepin County of Minnesota, retained an engineering consulting firm, HNTB Corporation, to further inspect the bridge, perform a load rating analysis, and design the necessary structural rehabilitation which ultimately included full replacement of the existing roadway deck and supporting spandrel cap beams. Over 30 rehabilitation options were considered before the design team decided to pursue an accelerated bridge construction approach.

Various factors attributed to this decision. It was determined that a rehabilitation using conventional methods would take 2 construction years to complete. Allowing the bridge to remain partially in service (i.e. using staged construction) was not practical due to the necessity of costly temporary shoring that would be required to support the unbalanced loads in the concrete arch system while only half of the bridge was loaded. Instead, the design team reached out to the local community to discuss the possibility of fully closing the bridge for a relatively short period of time using ABC techniques to rehabilitate the structure and re-open it to traffic as quickly as possible. The team determined that by using prefabricated elements, the bridge deck could be fully rehabilitated, and re-opened to traffic, in as little as 4 months.

While speed of construction was the driving factor for this project, there were other advantages to using a precast decking system. The precast deck would ultimately be of better quality than a cast-in-place option due to better control measures and curing conditions throughout fabrication. The precast system also allows the majority of concrete shrinkage to occur prior to deck installation, which drastically reduces the amount of shrinkage cracking in the deck. This, coupled with the use of epoxy-coated rebar and a polyester polymer concrete (PPC) overlay, would improve the durability and overall service life of the new deck.

Hence, prefabricated bridge elements connected with UHPFRC was chosen as the preferred solution for this project. The prefabricated elements included 43 precast concrete cap beams, 350 precast concrete deck panels, and 163 precast concrete ornamental railing panels. The project contractor, Kraemer North America, fabricated the cap beams and deck panels in a partially-controlled staging area adjacent to the project site. Approximately 4 to 5 deck panels were produced each day, starting in 2015. The panels were steam cured on-site and the edges blasted with high pressure water to remove the retarding paste and expose a rough aggregate finish. This type of finish is crucial for good bond to occur between the precast panel and field-cast UHPFRC [7].

The bridge was closed to traffic on May 8, 2016 at which point the contractor began to remove the existing 41-cm (16-in) thick concrete deck and spandrel caps (see Fig. 4). Once removed, the new precast cap beams were installed and the new 36-cm (14-in) thick deck panels were placed spanning from one spandrel cap to the next (see Fig. 5). Once the deck panels were placed in their proper sequence (see Fig. 6), forming was installed from the underside of the joint for the closure pour. The contractor opted to use a whaler type system using a vertical GFRP rebar to sandwich the forms against the top and bottom of the joint. This provided a tight seal which was crucial to ensuring the UHPFRC joints did not leak.

Figure 4: Franklin Avenue Bridge Deck Removal

Figure 5: New Precast Pier Cap

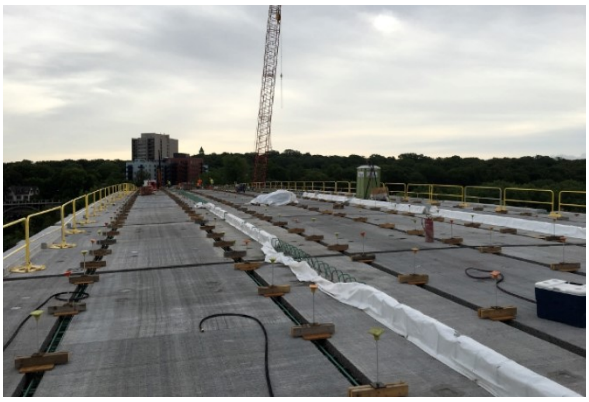

Figure 6: New Precast Deck Panels

For the UHPFRC placement, two 0.5-cubic meter (0.65-cubic yard) capacity portable mixers were used on-site to field-cast the material. The two mixers worked in tandem, so that when one mixer was beginning the 20-minute mixing process, the other was ready to discharge the material for placement (see Fig. 7). Once discharged, the material was transported to the closure pour location via motorized buggies and poured into the joint starting from the low end and working towards the high end (see Fig. 8).

Figure 7: Discharging UHPFRC from Mixer

Figure 8: Pouring UHPFRC Connection

Prior to placing the material in the joint, the existing precast surfaces within the joint were saturated with water to a saturated surface dry (SSD) condition (see Fig. 9). This is a necessary step to ensure that good bond develops between the precast element and the UHPFRC material [7]. To achieve this condition, the contractor utilized soaker hoses and misters to keep the interface wet prior to placement. When the joint was almost full of UHPFRC, the forms were installed along the top of the joints to contain the self-consolidating (i.e. flowable) material and prevent it from pouring out the low end of the joint. Once formed up, additional material was poured into a bucket which provided some hydrostatic pressure to ensure the joint was completely filled with material (see Fig. 10).

Figure 9: Precast Surface Prep

Figure 10: Top Forms with Bucket

In total, 268-cubic meters (350-cubic yards) of UHPFRC material was mixed and placed to complete this project. This was the first application of PBE with UHPFRC connections in the state of Minnesota. The bridge fully re-opened to traffic on September 1, 2016, only 116 days (17 weeks) after closing. The overall project construction cost was approximately $43 million USD, of which some federal funding was provided. [8] [9] [10]

4.2 U.S. Route 30 Bridge over Bessemer Avenue

The original Bessemer Avenue Bridge was a single span, reinforced concrete T-beam structure, built in 1930 (see Fig. 11). It had a span length of 16-meters (52-feet), carrying U.S. Route 30 over Bessemer Avenue approximately 18-kilometers (11-miles) east of Pittsburgh, Pennsylvania. The entire superstructure was in very poor condition due to heavy deterioration which included falling debris and a hole in the concrete deck.

Figure 11: Old Bessemer Bridge

Figure 12: New Bessemer Bridge

The bridge owner, the Pennsylvania Department of Transportation (PennDOT) – District 11, needed to replace the existing superstructure and retained an engineering consultant, HNTB Corporation, to design the replacement. Multiple constructability meetings were held in order to limit the number of design alternatives. The project faced some difficult challenges, including a high amount of traffic using the bridge on a daily basis, averaging approximately 20,000 vehicles per day. Additionally, there was limited right-of-way at the bridge, meaning there was no space to stage material or fabricate elements adjacent to the site.

An accelerated bridge construction method was necessary, given the bridge's heavy traffic and long detour route totaling 27-kilometers (17-miles). Staged construction (i.e. replacing the bridge in phases) was not feasible considering the severe deteriorated nature of the existing structure. Due to the limited space available, prefabricating the bridge elements, shipping them to site, and assembling them on-site was determined to be the optimum design/construction strategy in order to replace the structure as quickly as possible and minimize traffic disruptions.

The new superstructure (see Fig. 12) was a 16-meter (54-foot) long single span composed of six prefabricated modules, each consisting of 2 steel beams with a precast concrete deck. Steel beams and lightweight concrete were chosen to minimize the pick weight of each module and limit the crane size necessary to lift the modules in place (see Fig. 15). UHPFRC was used as the closure pour material in the longitudinal joints between the decks to connect the modules together (see Fig. 13). The closure pour was 20-cm (8-in) wide with a 15-cm (6-in) rebar lap splice length (see Fig. 14). No rebar hooks, hairpins, or heads were required to develop the bars due to UHPFRC's unique ability to fully develop straight reinforcing steel in very short lengths [6].

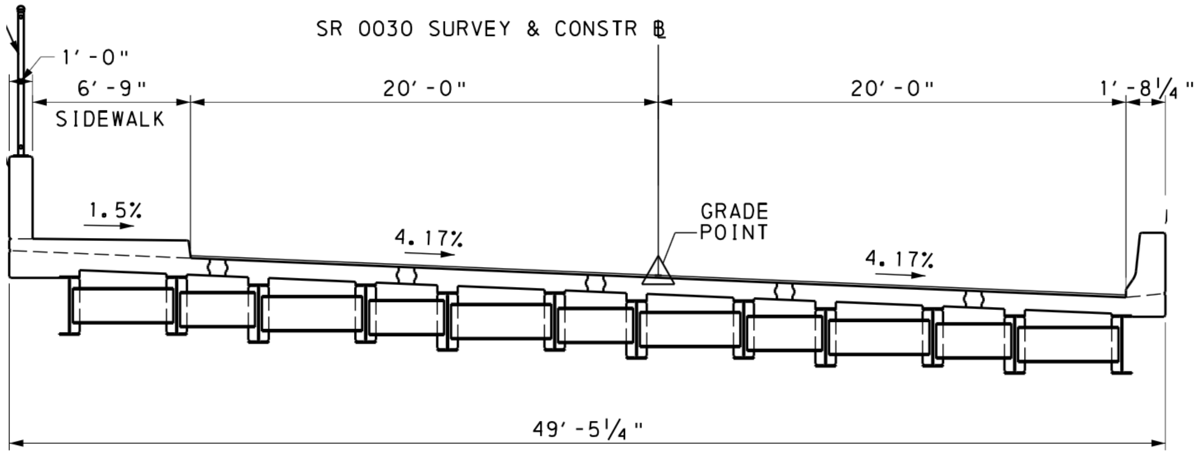

Figure 13: Typical Bridge Section (6-Modules with UHPFRC Closure Pours)

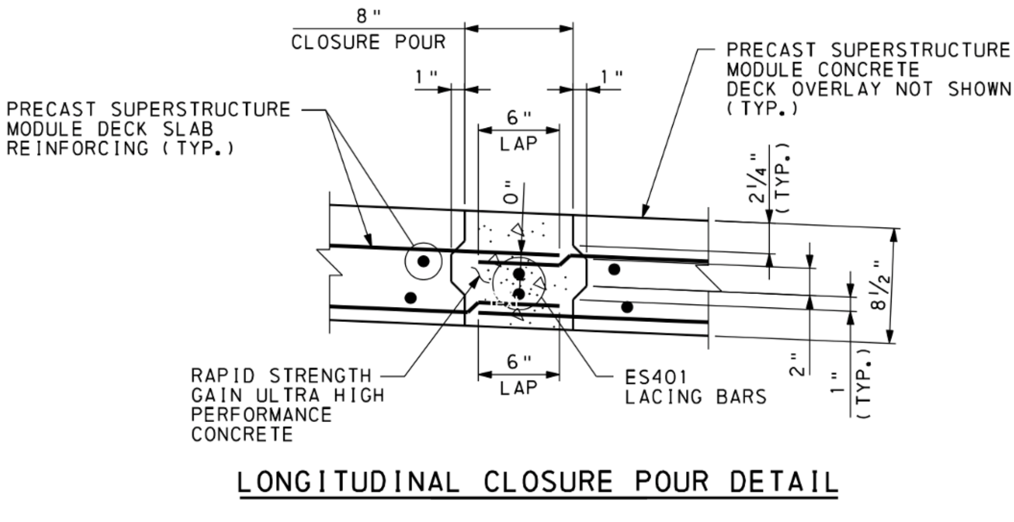

Figure 14: Closure Pour Detail

Two years prior to this project, PennDOT replaced a short arch bridge over Wampum Run using a similar ABC-PBE+UHPFRC approach which the contractor was able to construct during a 7-day closure period. Based on their experience with this past project, the DOT believed they could complete the Bessemer replacement in a shorter closure period since there was less substructure work involved. After a detailed analysis of the anticipated project schedule, it was believed feasible to complete the superstructure replacement during a single weekend road closure over a 57-hour period. The roadway would be closed at 21:00 on Friday evening and re-opened to traffic on Monday morning at 06:00, just in time for the morning rush hour commute.

In order to meet this accelerated schedule, a rapid-set UHPFRC formulation called Ductal® JS1212, manufactured and supplied by LafargeHolcim, was used (see Fig. 16). This material is capable of obtaining 83-MPa (12-ksi) compressive strength in just 12 hours when the internal curing temperature of the mix is maintained at 49-deg. C (120-deg. F). With this in mind, the contractor allotted 8 hours to form the joints, 6 hours to mix and place the 15-cubic meters (20-cubic yards) of UHPFRC, and 12 hours for the material to cure using external heat. External heat was provided via heating blankets placed on top of the joints and the internal curing temperature was monitored using thermocouples placed inside the joints.

Figure 15: Setting Exterior Module

Figure 16: Pouring UHPFRC Connection

To properly prepare for the UHPFRC placement, several things were done ahead of time by the contractor, Brayman Construction, to help mitigate construction risk and ensure a successful project in the short construction window provided. A UHPFRC test placement was performed prior to construction in order to simulate the expected on-site activities and become familiar with the material and forming requirements. The contractor also prepared a UHPC placement work plan, outlining the mixing, placing, and curing procedures that would be followed on-site. A dry fit-up of the prefabricated modules was performed at the precast facility prior to shipping them to site to ensure accurate fit-up in the field. Lastly, to ensure the high quality of the UHPFRC, an experienced Ductal® representative was present during all UHPFRC operations. All of this resulted in a production placement that went very smoothly and allowed the project to be completed on schedule. [11]

5. DESIGN REFERENCES

The following documents may be useful for designing an accelerated bridge construction project using prefabricated bridge elements and UHPFRC connections:

- *Accelerated Bridge Construction: Experience in Design, Fabrication and Erection of Prefabricated Bridge Elements and Systems,* HIF-12-013, 2011 [12]
- *Innovative Bridge Designs for Rapid Renewal: ABC Toolkit*, TRB, 2013 [13]
- *Design and Construction of Field-Cast UHPC Connections*, FHWA, 2014 [5]

6. CONCLUSIONS

- The use of UHPFRC in bridge projects in the United States continues to increase. Approximately 100 projects have been completed to date, demonstrating the material's superior performance and multiple benefits. Many years of research has proven that UHPFRC provides simple, strong, durable connections between prefabricated bridge elements such as precast concrete deck panels and prefabricated beam modules.
- A system that utilizes prefabricated bridge elements connected with UHPFRC can substantially accelerate the on-site construction schedule, resulting in significantly less user disruption, while also improving the long-term durability of the final structure.
- One example of a PBE-UHPFRC system is the Franklin Avenue Bridge project over the Mississippi River, which involved the rehabilitation of a bridge deck using precast concrete deck panels connected on-site using field-cast UHPFRC.
- Another excellent example is the U.S. Route 30 bridge project over Bessemer Avenue, involving the replacement of a bridge superstructure using prefabricated beam modules connected on-site using field-cast UHPFRC.

REFERENCES

[1] Graybeal, B., 'UHPC in the U.S. Highway Infrastructure: Experience and Outlook', UHPFRC 2013: Proceedings of the RILEM-fib-AFGC International Symposium on Ultra-High Performance Fibre-Reinforced Concrete (Proceedings PRO 87), (France, 2013), 361-370.
[2] FHWA, 'Ultra-High Performance Concrete: North American Deployments of UHPC in Highway Bridge Construction', www.fhwa.dot.gov/research/resources/uhpc/bridges.cfm
[3] ASCE, '2017 Infrastructure Report Card: Bridges', www.infrastructurereportcard.org/wp-content/uploads/2017/01/Bridges-Final.pdf
[4] Ruzzi, L. 'ABC Workshop: DelDOT/FHWA', Dover, DE (Sept. 2015).
[5] FHWA, 'TechNote: Design and Construction of Field-Cast UHPC Connections', *FHWA Publication No: FHWA-HRT-14-084*, McLean, VA, 2014.
[6] FHWA, 'TechNote: Bond Behaviour of Reinforcing Steel in Ultra-High Performance Concrete', *FHWA Publication No: FHWA-HRT-14-089*, McLean, VA, 2014.
[7] FHWA, 'TechNote: Bond of Field-Cast Grouts to Precast Concrete Elements', *FHWA Publication No: FHWA-HRT-16-081*, McLean, VA, 2016.
[8] Purnell, R., 'Perfecting Frank: Designers Restore Minn. Bridge Named after Designer', Roads & Bridges, (Nov. 4, 2016), 32-39.
[9] FIU-ABC-UTC, 'ABC Rehabilitation of Historic Franklin Avenue Bridge', webinar by Konda, T. and Sivakumar, B., Jan. 19, 2017, https://abc-utc.fiu.edu/mc-events/abc-rehabilitation-of-historic-franklin-avenue-bridge/?mc_id=229
[10] EDC, 'Project Case Study: Rapid Rehabilitation of a Mississippi River Crossing', www.fhwa.dot.gov/innovation/everydaycounts/edc_4/uhpc_ms_case_study.pdf
[11] FIU-ABC-UTC, 'PennDOT SR 30 over Bessemer Avenue Bridge Replacement in One Weekend', webinar by Myler, J., Ruzzie, L. and Sivakumar, B., Aug. 25, 2016, https://abc-utc.fiu.edu/mc-events/penndot-sr-30-over-bessemer-avenue-bridge-replacement-in-one-weekend/?mc_id=165
[12] FHWA, 'Accelerated Bridge Construction: Experience in Design, Fabrication and Erection of Prefabricated Bridge Elements and Systems', *Publication No. HIF-12-013, Highways for Life*, (Nov. 1, 2011).
[13] Transportation Research Board, 'Innovative Bridge Designs for Rapid Renewal: ABC Toolkit', *SHRP 2 Report S2-R04-RR-2* (2013).