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THE CONCRETE BRIDGE MAGAZINE

WINTER 2020

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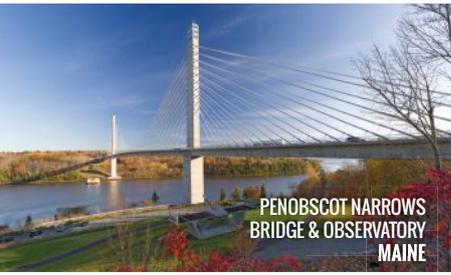
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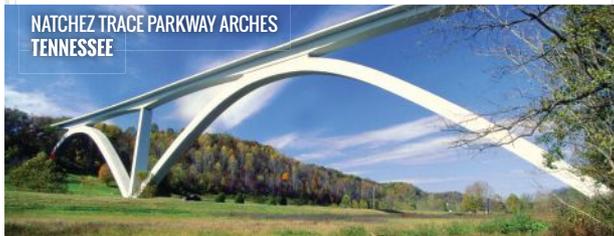
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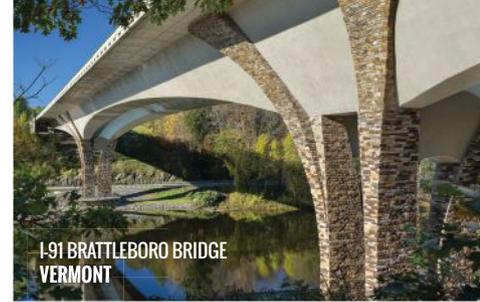
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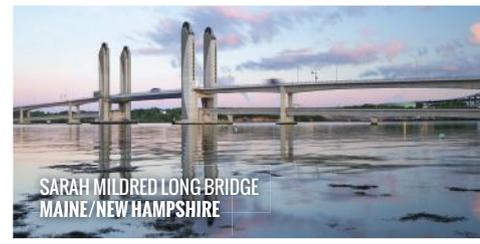
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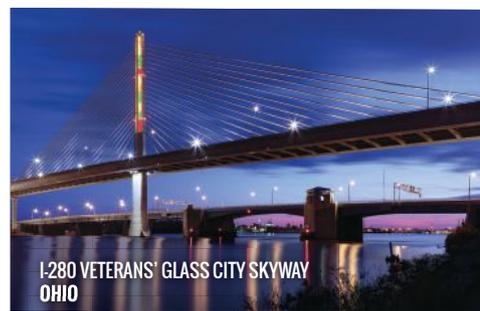
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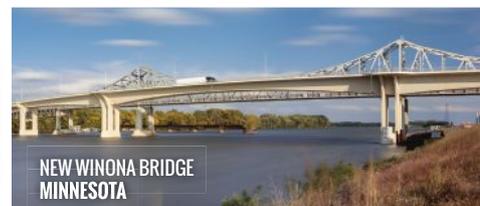
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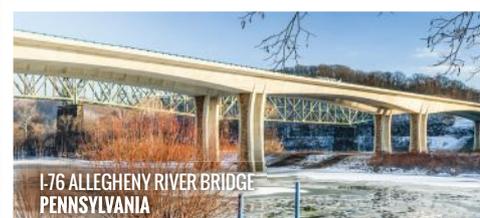
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SOUTH NORFOLK JORDAN BRIDGE  
VIRGINIA



Photo: Robert J. Healy.



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Photo: HDR.

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Photo: Alabama Department of Transportation.

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# Starting a Difficult Conversation

by William Nickas, Precast/Prestressed Concrete Institute, and Gregg Freeby, American Segmental Bridge Institute

On November 12, 2019, the National Transportation Safety Board (NTSB) released its final report on the Florida International University (FIU) pedestrian bridge collapse that occurred in 2018.<sup>1</sup> Reflecting on that report, we find ourselves asking, “How do we open needed discussions and share lessons from the tragedy for our industry as a whole?” It is time to break the ice and begin that process so we can move our industry forward.

## Key NTSB Findings and Recommendations

In all, the final NTSB report includes 30 findings and 11 recommendations. Table 1 shows the number of recommendations targeted to various parties.

**Table 1.** NTSB Recommendations Issued Following the FIU Bridge Collapse

Focus of Recommendation	No. of Items
Federal Highway Administration	1
American Association of State Highway Officials	3
Florida Department of Transportation	5
Designer	2
<b>Total</b>	<b>11</b>

Notably for our industry as a whole, the NTSB stated that the Federal Highway Administration (FHWA) must help the American Association of State Highway and Transportation Officials (AASHTO) address the “requirement that concrete bridge structures be designed with reasonable estimates for interface shear demand, the cohesion and friction contributions to interface shear capacity, and the clamping force across the interface shear surface.” Additionally, the three NTSB recommendations issued to AASHTO were to revise language in the *AASHTO LRFD Bridge Design Specifications* to improve:

- Concrete interface shear provisions
- Discussion of redundancy in the design of concrete structures

- Discussion of redundancy in the *LRFD Guide Specifications for the Design of Pedestrian Bridges*, with emphasis on uncommon structures

## Finding a Way Forward

A dear friend wrote to William one week after the collapse and shared, “The biggest issue to me has always been that an isolated failure gets seen by the public as a system-wide problem.” Although we are calling for industry-wide reflection, conversation, and action, it is important to note that the FIU pedestrian bridge was recognized throughout the NTSB hearings and the final report to be a unique structure. While the report does not directly state this, we believe the industry can feel confident that our traditional prestressed (pretensioned and post-tensioned) concrete I-, T-, and U-beams and box-section bridges that use basic structural beam theorems and rely on embedded, codified principles are working as intended.

The Florida Department of Transportation (FDOT) issued the following statement in October 2019 after an NTSB public meeting about the FIU tragedy:<sup>2</sup>

“The events surrounding the FIU bridge collapse are absolutely heartbreaking for both the families and loved ones of the victims, but also for the community and state,” said FDOT Secretary Kevin J. Thibault, P.E. “The Department has and will continue to cooperate fully with the NTSB as part of this process and has already implemented many of the improvements discussed today. I remain committed to ensuring that all NTSB recommendations are followed so a tragedy like this never happens again in Florida.”

We all must share this commitment. To address the 30 findings and 11 recommendations in the NTSB report, we must responsibly educate and retrain our existing workforce. We will also need to continue to attract qualified and experienced workers in both the design and construction areas. People are hard to find now, and the qualified labor shortage is only going to get worse. We will need to identify new approaches to recruit and retain the best people.

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The Terwillegar Park Footbridge over the North Saskatchewan River. Photo: Stantec.

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If you have a suggestion for a project or topic to be considered for *ASPIRE*, please send an email to [info@aspirebridge.org](mailto:info@aspirebridge.org)



American Segmental Bridge Institute



Epoxy Interest Group



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Wire Reinforcement Institute

Former FDOT Secretary Ben Watts (under whom William served while at FDOT) once said, "It takes a very long time to fill the public's reservoir of goodwill as it relates to infrastructure, but that reservoir can empty overnight. The public paints us all, engineers and contractors, with the same broad brush when an unfortunate incident occurs." In this issue of *ASPIRE*®, Leon Grant shares his perspective on how engineers in Canada have learned from another tragic bridge construction incident that occurred more than a century ago to embrace their professional responsibilities and demonstrate to the public that they deserve its goodwill.

As we close this editorial, we want to remind every engineer and every firm out there that each and every project has the potential to harm or boost our industry's public reputation. In future editorials, we will dive into other aspects of the NTSB findings with an eye toward lessons we all should learn.

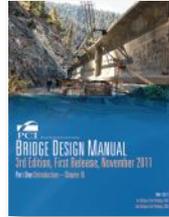
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1. National Transportation Safety Board (NTSB). 2019. *Pedestrian Bridge Collapse Over SW 8th Street, Miami, Florida, March 15, 2018*. Highway Accident Report NTSB/HAR-19/02 PB2019-101363. Washington, DC. <https://www.nts.gov/investigations/AccidentReports/Reports/HAR1902.pdf>.
2. Florida Department of Transportation. 2019. FDOT Statement on Today's NTSB Meeting; October 22, 2019 [press release]. Tallahassee, FL.



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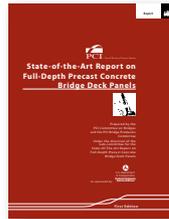


## PCI Bridge Design Manual

3rd Edition, Second Release, August 2014

This up-to-date reference complies with the fifth edition of the *AASHTO LRFD Bridge Design Specifications* through the 2011 interim revisions and is a must-have for everyone who contributes to the transportation industry. This edition includes a new chapter on sustainability and a completely rewritten chapter on bearings that explains the new method B simplified approach. Eleven LRFD up-to-date examples illustrate the various new alternative code provisions, including prestress losses, shear design, and transformed sections.

[www.pci.org/MNL-133-11](http://www.pci.org/MNL-133-11)



## The PCI State-of-the-Art Report on Full-Depth Precast Concrete Bridge Deck Panels

The *PCI State-of-the-Art Report on Full-Depth Precast Concrete Bridge Deck Panels* (SOA-01-1911) is a report and guide for selecting, designing, detailing, and constructing precast concrete full-depth deck panels for bridge construction. This report is relevant for new bridge construction or bridge-deck replacement.

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## CONCRETE CALENDAR 2020–2021

For links to websites, email addresses, or telephone numbers for these events, go to [www.aspirebridge.org](http://www.aspirebridge.org) and select the Events tab.

**January 12–16, 2020**

### ***Transportation Research Board Annual Meeting***

Walter E. Washington Convention Center  
Washington, D.C.

**February 3–7, 2020**

### ***World of Concrete***

Las Vegas Convention Center  
Las Vegas, Nev.

**March 3–7, 2020**

### ***PCI Convention with The Precast Show***

Fort Worth Convention Center  
Fort Worth, Tex.

**March 4–6, 2020**

### ***PTI Level 1 & 2 Multistrand and Grouted PT Specialist Workshop***

Miami, Fla.

**March 7, 2020**

### ***PTI Level 1 & 2 Multistrand and Grouted PT Inspector Workshop***

Miami, Fla.

**March 29–April 2, 2020**

### ***ACI Convention and Exposition***

Hyatt Regency O'Hare  
Rosemont, Ill.

**April 6, 2020**

### ***ASBI Grouting Certification Training Course***

J.J. Pickle Research Campus  
Austin, Tex.

**April 22–24, 2020**

### ***DBIA Design-Build for Transportation & Aviation Conference***

Hilton Anatole  
Dallas, Tex.

**April 27–29, 2020**

### ***fib Symposium on Concrete Structures for Resilient Society***

Shanghai, China

**May 3–6, 2020**

### ***PTI 2020 Convention & Expo***

Hilton Miami Downtown  
Miami, Fla.

**June 1–4, 2020**

### ***AASHTO Committee on Bridges and Structures Annual Meeting***

Branson Convention Center  
Branson, Mo.

**June 8–11, 2020**

### ***International Bridge Conference***

David L. Lawrence Convention Center  
Pittsburgh, Pa.

**June 22–25, 2020**

### ***Bridge Engineering Institute UHPC Symposium***

National University of Singapore  
Singapore

**August 2–6, 2020**

### ***AASHTO Committee on Materials and Pavements Annual Meeting***

InterContinental Hotel Miami  
Miami, Fla.

**September 13–16, 2020**

### ***AREMA Annual Conference***

Hilton Anatole  
Dallas, Tex.

**September 23–26, 2020**

### ***PCI Committee Days and National Bridge Conference***

Loews Chicago O'Hare Hotel  
Rosemont, Ill.

**October 6–9, 2020**

### ***PTI Committee Days***

JW Marriott Cancun  
Cancun, Mexico

**October 25–29, 2020**

### ***ACI Fall 2020 Conference***

Raleigh Convention Center  
& Raleigh Marriott  
Raleigh, N.C.

**October 26–28, 2020**

### ***ASBI 32nd Annual Convention and Committee Meetings***

Hyatt Regency Austin  
Austin, Tex.

**January 24–28, 2021**

### ***100th Transportation Research Board Annual Meeting***

Walter E. Washington  
Convention Center  
Washington, D.C.

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# Full-Service Engineering

Stantec's bridge division serves clients' bridge needs from conceptual design through inspection, maintenance, and rehabilitation, using whatever techniques are required.

by Craig A. Shutt

Stantec is recognized around the world for providing a wide range of architectural and engineering solutions. Its North American bridge division enhances that reputation by providing a full complement of bridge engineering services, from concept to rehabilitation.

"In the bridge sector, we pride ourselves on being a full-service company in all aspects of bridges," says Tony Hunley, vice president in Stantec's bridge sector. "We're not just known as new-bridge designers. We do it all."

Reed Ellis, vice president and bridge sector leader adds, "One thing that sets us apart is the complete range of bridge engineering services we provide our clients through all stages of a bridge's life cycle. That includes inception, planning, conceptual design, design, and construction. It continues through regular and rope-access inspections, maintenance, repair, rehabilitation, load rating, and strengthening. We also implement bridge management systems, help bridge owners manage and prioritize repairs, and decommission structures."

Given this range of services, Stantec establishes strong ties with departments of transportation (DOTs) and other owners that last after a specific project ends. "We form long-standing relationships, becoming a partner and consultant over the long term on that structure," says Ellis.

## Expanding Inspection Services

Bridge inspections have been a recent area of growth for Stantec. "In the past 10 years, we've seen a considerable increase globally in owners wanting to inspect their bridges to improve their asset management," says Ellis.



Using rope access, Stantec performed the first routine inspection on the 1896-ft-long Mike O'Callaghan-Pat Tillman Memorial Bridge in 2013. The bridge is 870 ft above the Colorado River. All Photos: Stantec.



The Terwillegar Park Footbridge consists of 86 precast concrete deck panels supported by bearing cables cast into the deck with 7.3-ksi high-performance cast-in-place concrete.

Frequently, inspections require a variety of approaches, including rope access.

**“In the past 10 years, we’ve seen a considerable increase globally in owners wanting to inspect their bridges to improve their asset management.”**

“Our philosophy for inspections is to use the most effective accessibility techniques necessary to ensure we see everything. We often combine mechanical access equipment, such as underbridge and snooper trucks, with rope-access techniques, especially on major bridges,” says Ellis.

Such inspections can create challenging situations. This was the case during the inspection of the 1896-ft-long Mike O’Callaghan–Pat Tillman Memorial Bridge, 870 ft above the Colorado River and downstream from the Hoover Dam. Working for the Nevada Department of Transportation, Stantec provided the first routine inspection of the massive structure while under live traffic in 2013, and then inspected it every other year through 2019.

In 2019, the inspection crew finished its work on the concrete, open-spandrel arch structure in only six days, using rope access. The structural engineering climbing team followed practices of



The Terwillegar Park Footbridge over the North Saskatchewan River is Canada’s longest stress-ribbon bridge, spanning 859 ft 6 in. The structure is the first of its kind in Edmonton, Alberta, and the northernmost bridge of this type in the world.

the Society of Professional Rope Access Technicians, Ellis notes. “It was a complex, hands-on inspection.”

The company is evaluating new inspection tools, including drones. “We’re looking internally to see how we can best utilize them to provide the appropriate level of inspection for each bridge,” says Ellis. “They definitely show promise, but we have to determine what value is there and if we can use them effectively.”

### Rehabilitation Work

The growth in inspections has in turn led to an increase in rehabilitation work. “Often, DOTs are looking to extend the service lives of their existing bridges rather than replacing them completely,” Ellis says.

Bridge decks are usually the first area targeted for replacement, but joints typically receive the most attention. “Joints are the number-one challenge for existing bridges, because they can lead to deterioration of the underlying girders and substructure piers and caps. The biggest part of our rehabilitation work is addressing deterioration under the joints,” says Ellis. To aid that work, Stantec incorporates new patching techniques and protections, such as galvanic anode and other active cathodic protection systems.

Hunley currently is leading Stantec’s work on a major bridge rehabilitation and replacement initiative for the Kentucky Transportation Cabinet. To reduce the number of substandard bridges, which reached more than 1000 in 2018, Kentucky launched Bridging Kentucky, an ambitious six-year, \$700 million program designed to restore state and locally owned bridges.

Stantec is serving as the prime consultant, along with QK4 Inc. and AECOM as lead partners. The project team also includes 22 engineering, environmental, and specialty firms. “We are performing a full-service effort: program management, evaluation, asset management prioritization, rehabilitation or replacement designs, and construction-phase support,” Hunley says. The firms are taking a programmatic approach, bundling bridges by type and location rather than letting contracts bridge by bridge, and they are using both traditional design-bid-build and design-build contracts.

A customized life-cycle cost evaluation was performed for each bridge considered for rehabilitation or replacement, which determined that about 40% of the structures could be rehabilitated. As of August 2019, Kentucky had awarded \$113.8 million in construction contracts for 190 bridges, and its costs were more than



The precast concrete deck panel design combined with the use of high-performance cast-in-place concrete allowed the Terwillegar Park Footbridge to maintain a thin deck profile that minimized the environmental and visual impact of the bridge on the North Saskatchewan River valley.

20% below anticipated budgets. By mid-2020, contracts for more than 450 bridges will be let.

Kentucky's rehabilitation projects are designed for a minimum design service life of 30 years. Concrete repair methods for these projects will involve determining the best patching approach, resolving the source of the deterioration, and proactively protecting new and existing concrete surfaces from water and chloride infiltration by sealing repaired substructure concrete with a high-quality epoxy-coating system.

Since the launch of Bridging Kentucky, more than 150 additional bridges have been determined to be substandard due to condition or necessary weight restrictions. "Kentucky was slowly losing ground to deterioration faster than it could replace bridges," Hunley says. "By addressing 1000 of the worst bridges in the inventory in a short period of time, the Bridging Kentucky program will allow the state to turn the tide and be in a position to maintain and improve the overall condition of their bridges into the future." (See the Fall 2019 issue of *ASPIRE*® for a State article on Kentucky with more details of the Bridging Kentucky program.)

### Signature New Construction Projects

At the other end of the spectrum, Stantec has recently been involved in

major new bridge projects, including projects using alternative project delivery methods, such as design-build and public-private partnerships.

"DOTs have tight budgets, and while they are stretching their resources, they also have to address their biggest problems, and that often means their largest or most complex bridges or major corridor improvements that include a large number of bridges," says Hunley. "What we don't see as much right now is the average, routine bridge replacement. There are far fewer of those being done individually."

**"What we don't see as much right now is the average, routine bridge replacement. There are far fewer of those being done individually."**

One notable construction project is the Terwillegar Park Footbridge over the North Saskatchewan River in Edmonton, Alberta. Stantec designed this bridge—Canada's longest stress-ribbon bridge and the second longest in the world—to link Terwillegar Park with an existing trail system on the other side of the river. Spanning 859 ft 6 in., the structure is the first of its kind

in Edmonton and the northernmost bridge of this type in the world.

"This bridge structure was only possible through advancements in concrete products," says Ellis, who served as project leader. "The City challenged engineering firms to propose a solution that would be innovative, have a low impact on the river valley both environmentally and visually, and then achieve these goals within a tight budget and timelines."

The stress-ribbon bridge achieved the goals by using precast, prestressed concrete. "It allowed for efficient and cost-effective construction, producing a slender and elegant bridge form."

The superstructure consists of 86 precast concrete deck panels and is supported by bearing cables cast into the deck with 7.3-ksi high-performance cast-in-place concrete. This design allowed the panels to be cast only 16.3 in. thick. "This option was the most economical and best met the City's vision and sustainability goals. And it was delivered on schedule and within budget."

Design-build delivery methods often provide the best approach for large projects, Hunley notes, as they allow the design team to leverage their expertise and collaborate with the contractor to create efficiencies. That approach worked well for the U.S. Route 460 Connector project on the Virginia-Kentucky border through the Appalachian Mountains. The project included the Grassy Creek Twin Bridges, two six-span, 1733-ft-long structures that feature a four-span cast-in-place segmental concrete box-girder unit with 489-ft-long main spans and two approach spans with precast concrete I-beams. The depths of the segmental box girders varied from 12 ft 6 in. at midspan to 30 ft 3 in. at the piers.

For this project, Stantec managed field surveying; geotechnical, roadway, and structure design; permitting; right-of-way planning and mineral acquisition; and relocation of utilities and a small cemetery. At more than 250 ft high, the two cast-in-place, post-tensioned segmental bridges are the highest in Virginia.



Stantec was the overall project design manager in a design-build contract for the Grassy Creek Twin Bridges, a part of the U.S. Route 460 Connector project in Virginia. Each of the two 1733-ft-long bridges features a four-span post-tensioned segmental concrete box-girder unit and two approach spans with precast concrete I-beams.

"The key challenge was the extremely steep mountain slopes at each end," explains Hunley. "We used long spans to minimize the impact of cutting into the slope to create foundations and potentially undermine the next pier. Terrain issues were a huge concern and drove the design and construction methods."

The segments were constructed from the top down, using a form traveler along with tower cranes. "We needed as much access as we could achieve in an isolated area," Hunley says. "It was unusual to see tower cranes usually used for tight, urban high-rises working in this very rural location." (See the Fall 2014 issue of *ASPIRE* for a Project article on the U.S. Route 460 Connector.)

## Leveraging the Benefits of Concrete

These projects show some of the ways Stantec has been leveraging concrete's capabilities to meet bridge challenges. "Concrete designs are preferred by many owners," notes Hunley. "There are always regional preferences, but it is the workhorse for small- to medium-span bridges. We can tailor it to their needs, and they see durability and reduced life-cycle costs."

Service life is a dominant focus today among owners. "For major bridges, they're often looking to achieve 100 years of service in the initial design and construction," says Hunley. For that reason, Stantec designs projects with long-term maintenance in mind. "We emphasize clean, simple details, eliminating joints, and using replaceable bearings."

**"We emphasize clean, simple details, eliminating joints, and using replaceable bearings."**

Concrete suppliers are aiding that work. "There is more attention paid to mix designs, admixtures, exposure zones, and salt resistance," explains Hunley. "We're providing more reinforcement bar cover and increased corrosion-resistant reinforcement to aid those changes, and suppliers are responding with concrete mixtures with higher strength and improved beam shapes, which are helping us meet the needs."

## ABC Solutions

New techniques are needed to meet current and future challenges. "The biggest challenge we face today is designing in difficult conditions under ongoing traffic," says Hunley. "Accelerated bridge construction (ABC) methods are becoming vital to minimize construction delays."

Stantec has used a variety of ABC approaches, including prefabricating as many components as possible to assemble quickly at the site. "This approach is used most often where there are lower volumes of traffic," says Hunley. Stantec recently completed

## Stantec's Service

Stantec was founded in 1954 as D.R. Stanley Associates in Edmonton, Alberta, by Donald Stanley, the first Canadian to earn a PhD in environmental engineering. After expanding through a variety of acquisitions, the company was reorganized in the early 1990s as the Stanley Technology Group. The company went public in 1994 as Stantec.

Stantec has continued to expand through acquisitions, adding more than 130 firms since it went public. It has approximately 22,000 employees operating out of more than 400 offices in North America and globally.

two ABC projects in Connecticut using precast concrete elements for abutments and wingwalls.

The company also has been involved with sliding structures into place using various types of equipment. "Owners are becoming more aggressive in returning roads to users quickly, so they're looking at more options. As some become comfortable using ABC, other owners are warming to it when they look for those benefits too."

One such project was the Interstate 84 Bridges over Marion Avenue in Southington, Conn., where all three lanes of traffic in each direction had to remain open during construction. The twin bridges featured Prestressed Concrete Committee for Economic Fabrication (PCEF) 47-in.-deep beams. Two sets of self-propelled modular transporters—one for each bridge—were used on the project. (See the Summer 2015 issue of *ASPIRE* for a Project article on these bridges.)

Staying open to new ideas and adopting new techniques will keep Stantec moving forward. "We anticipate an increase in more efficient concrete beam shapes to extend spans even further," says Hunley. "We're seeing more shapes being tried by several owners. And more DOTs are gaining comfort levels with accelerated bridge construction, post-tensioned concrete bridge designs, and enhanced rehabilitation strategies for extending service life of bridges." 



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# Rapid Bridge Replacement Lessons Learned

PennDOT's \$1.1 billion, 558-bridge replacement program produced many lessons that will help the commonwealth—and other states—on future projects

by Tom Macioce, Pennsylvania Department of Transportation

The Pennsylvania Department of Transportation (PennDOT) has one of the largest and oldest bridge inventories in the country. In summer 2019, Plenary Walsh Keystone Partners (PWKP), the development entity on PennDOT's major Rapid Bridge Replacement (RBR) project, started construction on the project's final bridge. This multiyear, \$1.1 billion program allowed PennDOT to fully replace 558 poor-condition structures.

## Choosing a Public-Private Partnership

The project was accomplished through a comprehensive public-private partnership (P3) arrangement. The consortium of companies in PWKP included Plenary Group USA Ltd. and Walsh Investors LLC, which are providing financing and long-

term management; a joint-venture lead construction team of Walsh Construction Company and Granite Construction Company; HDR Inc., the lead design firm; and Walsh Infrastructure Management, which will provide maintenance on the completed bridges for 25 years.

More than 2000 poor-condition PennDOT-owned bridges were screened prior to issuing the request for proposals (RFPs). A host of factors were considered in the screening process, including a bridge's age, length, number of lanes, and average daily traffic, as well as the structure's impact on utilities, railroads, and the environment. Most of the bridges selected were small—mostly single-span, two-lane structures—with similar characteristics.

Developing the P3 required significant effort involving requests for information, RFPs, the actual contract, and the development of the technical provisions. More than 1000 documents were saved in 29,000 files, requiring 37 gigabytes of memory.

Four teams were invited to submit final proposals, and the PWKP team was ultimately chosen based on scoring that considered cost as well as the team's financial capability, background, experience in managing comparable projects, understanding of the work involved, and technical approach.

Construction began in 2015. PennDOT's RBR project was the first in the nation to bundle the full replacement of hundreds of bridges in a single P3 agreement.

The bridge carrying Kirks Mill Road (Route 2002) over Reynolds Run in Little Britain Township, Lancaster County, Pa., was replaced in August 2018. Located near the Kirks Mills Historic District, this project required extra coordination and monitoring efforts. All Photos: Pennsylvania Department of Transportation.





The State Route 34 Bridge over Hunters Run in Cumberland County, Pa., is on the Appalachian Trail and required extensive interagency coordination to address design and construction concerns.

The P3 model promised enticing benefits. In addition to leveraging private investment funds, it was expected to increase efficiency by focusing contracts on bridges of similar size and design, which would allow components to be mass-produced, resulting in time and cost savings.

Unfortunately, actual efficiencies did not match projections due to a variety of reasons. With such a large-value contract and a new delivery method, there were bound to be challenges, unforeseen issues, conflicts to resolve, and nonconformances.

### Scheduling Challenges

The requirements for the RBR project were significant, and PWKP essentially assembled a department-of-transportation-like organization within six months to perform preliminary engineering, final design, letting of subcontracts, construction, inspection, and maintenance.

Above all, the project was driven by scheduling, and the partnership hoped to derive key benefits from grouping bridges in a geographic region. However, to advance construction effectively, some bridges were delayed,

ending the geographically coordinated effort. PWKP chose to bid many bridges to subcontractors, and this change resulted in many bridges being bid one at a time.

Also, the bridges had varying degrees of complexity, similar to PennDOT's regular program. Some sites were complex and therefore required more extensive planning and additional time to design and/or construct. Complexities included railroads, consideration of historic sites, difficult right-of-way acquisitions, and multiple aerial and subsurface utility relocations.

**Table 1.** Existing Bridge Types Replaced with PennDOT's Rapid Bridge Replacement Project

Bridge Superstructure Type	Number of Bridges Replaced	Subtotal (Percentage of Total Bridges)
Cast-in-place concrete T-beams	200	
Cast-in-place concrete slab or frame	55	
Prestressed concrete box beams	39	
Cast-in-place concrete closed spandrel deck arch	19	
Precast concrete channel beams	4	
Prestressed concrete I-beam	1	
<b>Replaced concrete superstructure subtotal</b>		<b>318 (57%)</b>
Steel beams or girders	165	
Concrete encased steel beams	68	
Steel through truss	3	
Steel pipe arch culvert	1	
<b>Replaced steel superstructure subtotal</b>		<b>237 (42%)</b>
Masonry closed spandrel deck arch	3	
<b>Replaced other superstructure subtotal</b>		<b>3 (1%)</b>
<b>TOTAL</b>	<b>558</b>	

Source: Table compiled from data at [www.dot.state.pa.us/public/Bureaus/Pres/P3/P3RBRBridgeList.xlsx](http://www.dot.state.pa.us/public/Bureaus/Pres/P3/P3RBRBridgeList.xlsx).

With "rapid" included as a key metric in the project, PennDOT established limited construction times for projects that contained detours to minimize the impact on the traveling public. Depending on the type of structure, traffic closures were set at 12, 75, or 110 days. If bridges did not meet these schedules, monetary penalties were incurred. In addition, there were incentives, in the form of accelerated availability payments, to complete bridges ahead of schedule.

To allow construction to begin as soon as possible, PennDOT developed conceptual plans and hydrologic and hydraulic reports, and acquired waterway permits and right-of-way for 87 bridges earmarked for early completion. PWKP then developed final design plans and built these bridges. However, PWKP chose to revise roughly half of the conceptual plans, which meant that the waterway permits

**Table 2.** Replacement Bridge Types Constructed under PennDOT’s Rapid Bridge Replacement Project

Bridge Superstructure Type	Number of Replacement Bridges	Subtotal (Percentage of Total Bridges)
Prestressed concrete box beams	342	
Precast concrete culvert	177	
Prestressed concrete bulb tee	17	
<b>Constructed concrete superstructure subtotal</b>		536 (96%)
Folded steel plate girder	7	
Steel beam	3	
<b>Constructed steel superstructure subtotal</b>		10 (2%)
Other	12	
<b>Constructed other superstructure subtotal</b>		12 (2%)
<b>TOTAL</b>	<b>558</b>	

Source: Table compiled from data received from Walsh-Granite.

required revisions, delaying the start of construction.

### Documentation and Informational Challenges

One basic need for the project was a data and document management system. PWKP selected a different system than that used by PennDOT. Had both parties used the same system, construction management probably would have functioned more efficiently.

Another challenge involved the concise definition of the key contractual design information. PennDOT provided the traveled-way geometry (number of lanes, lane widths, shoulder widths, and sidewalks), and the traffic restrictions—namely, whether staged construction or detours would be used, detour duration, road-users liquidated damages, and other restrictions, such as calendar restrictions. However, the concise nature of the contractual design requirements led to mixed results. For example, on smaller bridges, providing one soil test boring per substructure unit produced a successful outcome, but some restrictions were not as clearly defined as intended, eventually resulting in change orders.

### Determining Risk Decisions

Deciding which approvals to retain and which to transfer to PWKP was a key risk decision for PennDOT. The contract gave PennDOT approval authority on prefinal design-type submissions to ensure that the bridge and roadway geometries were properly designed, but the final design was completed by

PWKP and did not require PennDOT’s approval.

The bridge specifications were written to be prescriptive, while other disciplines, such as roadway design, were afforded more flexibility. Limited options for several bridges where design issues arose resulted in difficulty achieving approvals.

### Inspection Challenges

Because the design was managed in Pittsburgh, where PWKP is based, and PennDOT is based in Harrisburg, weekly shoulder-to-shoulder meetings were established.

For on-site inspection, an independent quality-acceptance firm hired by PWKP was used. This firm reported to both PWKP and PennDOT; it did not report to the construction joint-venture. The decision to transfer quality-acceptance inspections to a design-build team required careful and comprehensive considerations. While PennDOT would not necessarily preclude the use of design-build team quality-acceptance

inspections on future P3 projects, the contract requirements would be modified from the RBR project.

During the first two years of the project, individual quality-acceptance inspectors were responsible for up to three or four bridges, with scheduling based on their presence at key construction activities identified as “hold points.” To improve inspection quality, one inspector was assigned per bridge for all bridges constructed after the second year.

### Maintenance Phase

For 25 years PWKP will maintain waterway channels 50 ft upstream and downstream of each bridge, and will perform annual cleaning of bridge decks and beam seats on a five-year cycle. A maintenance plan, including maintenance of the guiderail system, pavement, and bridge structure, was developed for each bridge. PWKP will also perform the required National Bridge Inspection Standards biennial bridge inspections.

In the interest of cost-effectiveness, PennDOT kept certain maintenance items in-house. For example, PennDOT crews will plow snow from bridges because they are already clearing roadways.

PennDOT anticipates that on future P3 projects, guiderail and pavement maintenance may be retained in-house because PennDOT believes it can perform this work more efficiently than a contractor could.

As bridges opened to traffic, maintenance phases began. With the 25-year maintenance term, the first bridge will be returned, or “handed back,” to PennDOT in 2040. Some features, such as the asphalt approach

Spanglers Mill Road Bridge crosses Yellow Breeches Creek in Cumberland County, Pa., a waterway used recreationally for boating and fishing. The bridge site was the location for the October 2014 press event announcing selection of Plenary Walsh Keystone Partners for the public-private partnership agreement.



pavement, will be returned after five years.

Approximately one year in advance of handing back a bridge, a joint PennDOT-PWKP inspection will be conducted to determine the condition rating of key elements of the bridge. As per the contract terms, 98% of the bridges must have a condition rating of at least 7 for all elements, and 100% of the bridges must have a condition rating of at least 7 for the superstructure.

### Payment Structure

During the design and construction terms of the project, PWKP was paid by PennDOT through a mobilization payment, milestone payments, and availability payment made as bridges were constructed and opened to traffic. In addition, PWKP leveraged funds from shareholders in the consortium and from lenders. With these payments, PWKP pays the design and construction joint venture of Walsh-Granite and the

maintenance entity, Walsh Infrastructure Management. Then, in the maintenance term, PennDOT will pay availability payments over a 25-year period.

### Accelerated Delivery

The RBR project provided an opportunity to accelerate the delivery of replacements for poor-condition bridges. By focusing on bridges of similar size and design (typically, single-span bridges or culverts), PennDOT and PWKP could use similar designs and achieve economies of scale, optimizing the ability to complete the design and construction of individual bridges more quickly. PennDOT estimates that a comparable replacement project using conventional contract procedures would have taken 8 to 12 years, whereas this P3 project compressed the schedule to approximately 5 years.

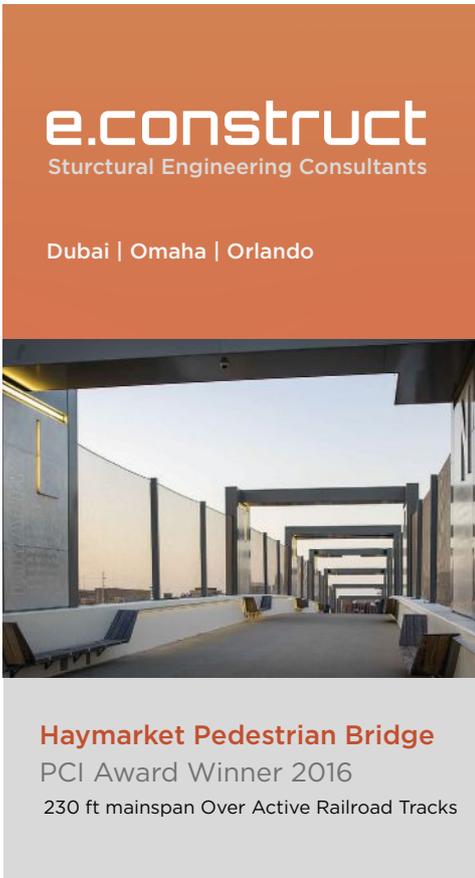
### Lessons Learned

All projects bring with them an opportunity to learn. Given the alternative delivery vehicle used to

procure a private partner, as well as the project's size (558 individual locations across the entire state of Pennsylvania), the RBR project provided numerous opportunities for PennDOT to experience new ways of managing and coordinating projects; learn or adapt processes to expedite project development; improve internal and external communications; and gain a better understanding of how performance-based contracting works.

Overall, this project achieved PennDOT's key goals of accelerating construction for the replacement of poor-condition bridges, minimizing impacts on the traveling public, continuing to ensure public safety, and improving system connectivity and mobility for commerce. It provided an approach that could be used again with lessons learned from this project implemented. 

*Tom Macioce is chief bridge engineer for the Pennsylvania Department of Transportation in Harrisburg.*



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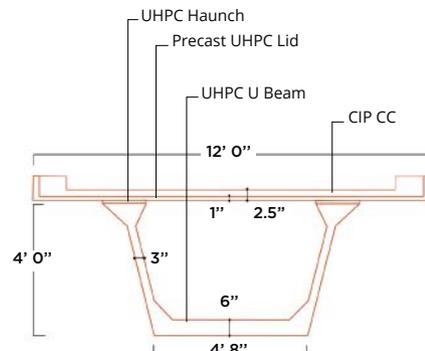
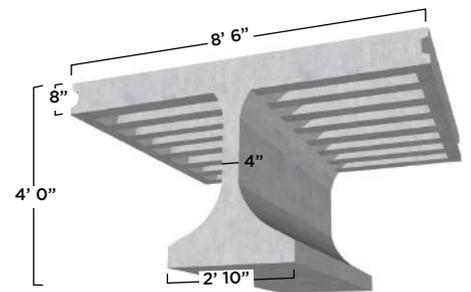
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## PROJECT

# Christina River Bridge, Wilmington, Delaware

by Robert J. Healy, RK&K, and Jason Hastings, Delaware Department of Transportation

The Christina River Bridge project is part of a revitalization effort to improve the Wilmington, Del., riverfront. This area had a long history of shipbuilding and other industries but fell into disuse as local industry declined in the decades after World War II. In recent years, the area has been redeveloped with many commercial, residential, and recreational features, including a Minor League Baseball stadium for the Wilmington Blue Rocks, hotels, apartments, restaurants, and shops. A riverwalk path along the river's west bank provides pleasurable access to all these amenities, extending from downtown Wilmington to a wildlife preserve to the west. The new multimodal Christina River Bridge connects the redeveloped riverwalk attractions along the west bank and the current industrial area on the east bank, with the hope of spurring further redevelopment in this area. The bridge will also alleviate traffic congestion and improve mobility and circulation for the riverfront community by introducing additional access to U.S. Route 13, Interstate 495, and Interstate 95.

### Geographic Considerations

The new bridge is located at the far western end of the current west bank development. A network of streets within the riverfront development is being extended to improve internal traffic flow and provide additional access



Cofferdam at bridge pier 2 showing 30-in.-square concrete piles and one of the precast concrete bottom soffit form slab segments being placed. Photo: R.E. Pierson Construction Company.

points to major highways not currently connected to the riverfront. Initial location studies aimed to make the river crossing as direct as possible, connecting to the logical available termini on both ends. However, this strategy would have placed the bridge too close to developed property; ultimately, a skewed crossing was chosen.

The Christina River is considered navigable in this area of Wilmington, and the navigational clearance requirements

dictated a 150-ft-wide channel and a 14-ft-high underclearance. Along the proposed skew, a main span of 180 ft was necessary to provide the required clearance. The Christina River, located close to the Delaware River and Bay, experiences a rather large 5 ft swing in tides between mean high water and mean low water. Stakeholders wanted a low profile for the bridge and roadway to keep the bridge as safe and unobtrusive as possible, simplify multimodal connections to the bridge,

## profile

### CHRISTINA RIVER BRIDGE / WILMINGTON, DELAWARE

**BRIDGE DESIGN ENGINEER:** RK&K, Baltimore, Md.

**CONSTRUCTION MANAGEMENT/INSPECTION:** AECOM, Mechanicsburg, Pa.

**PRIME CONTRACTOR:** R.E. Pierson Construction Company, Pilesgrove, N.J.

**CONTRACTOR'S CONSTRUCTION SPECIALTY ENGINEER:** McNary Bergeron & Associates, Old Saybrook, Conn.

**PRECASTER:** Precast Systems Inc., Allentown, N.J.—a PCI-certified producer

**POST-TENSIONING CONTRACTOR:** Freyssinet, Sterling, Va.



Erection of a haunched pier segment at pier 1. Note the temporary bent in the river being used to temporarily support pier segments. Photo: R.E. Pierson Construction Company.

and preserve skyline views of downtown Wilmington along the riverwalk.

This combination of geometric constraints posed a challenge for the bridge superstructure design. Initially, a three-span continuous steel girder bridge was investigated and proposed for this site. However, the bridge owner wanted a low-maintenance and

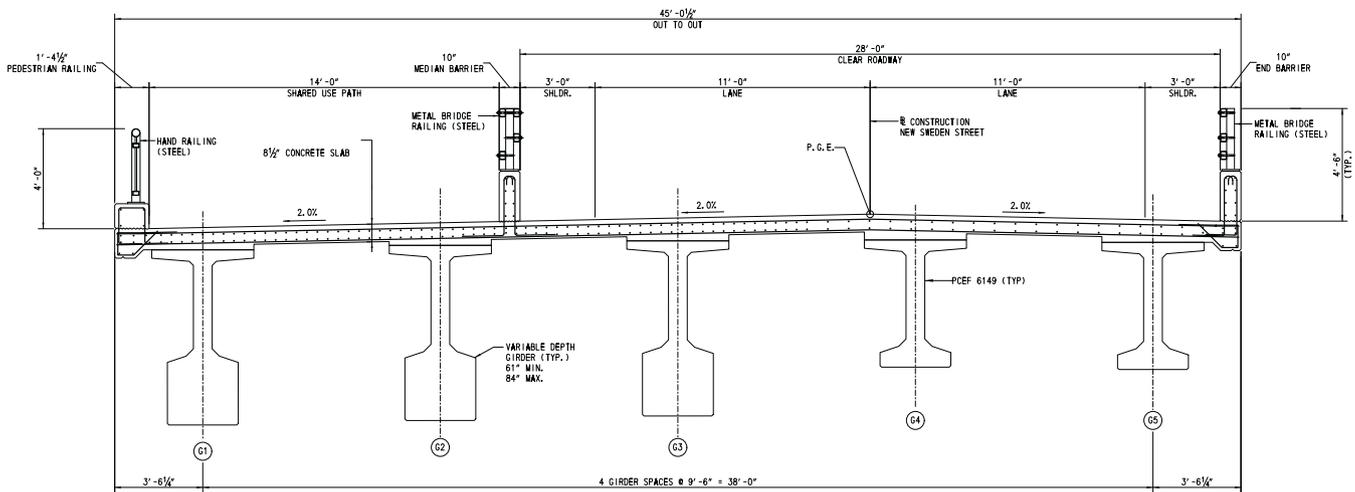
durable bridge that would minimize future maintenance and not require painting. Concrete girder options were investigated, but the depth of available standard bulb-tee girders that would provide the 180-ft span and meet the underclearance requirement and tidal range would lead to an undesirably high bridge profile. The solution was to provide a more customized

design using fully continuous, spliced pretensioned and post-tensioned concrete bulb-tee girders with haunched segments at the piers. This solution was not the most efficient section, but it met all structural and geometric constraints.

### Project Specifications

The Christina River Bridge comprises three spans (145 ft, 180 ft, 145 ft), for a total length of 470 ft. It is 45 ft wide, carrying two 11-ft-wide lanes of New Sweden Street along with a barrier-separated, 14-ft-wide shared-use path. The bridge alignment is straight but skewed at approximately 65 degrees to the river and on a vertical curve with approach grades of 3.5% and 4.3%.

The typical section has five lines of girders spaced at 9 ft 6 in. with 3 ft 6 in. overhangs. The girders are 5 ft 1 in. deep and are haunched in a straight-line taper to a depth of 7 ft 0 in. at each pier. The spliced girders consist of pretensioned precast concrete bulb-tee segments that are post-tensioned



The spliced girders consist of pretensioned precast concrete bulb-tee girder segments that are post-tensioned after splicing. They support an 8.5-in.-thick, cast-in-place concrete deck, 4-ft-6-in.-tall roadway barriers with concrete bases and steel railings, and a 4-ft-tall pedestrian railing at the bridge fascia next to the shared-use path. Left side of figure is section at pier; right side is section at midspan and abutments. Figure: RK&K.

### DELAWARE DEPARTMENT OF TRANSPORTATION, OWNER

**BRIDGE DESCRIPTION:** Three-span (145 ft, 180 ft, 145 ft) continuous, spliced, prestressed, post-tensioned concrete bulb-tee girder bridge with two 11-ft-wide roadway lanes and a barrier-separated 14-ft-wide shared-use path; cast-in-place concrete frame underpass, 50 ft long and 45 ft wide; concrete retaining walls at roadway approaches; and a cast-in-place concrete stairway connecting the bridge to the shared-use trail below

**STRUCTURAL COMPONENTS:** Precast, prestressed haunched concrete bulb-tee girders, spliced and post-tensioned for full dead and live load continuity; five girder lines consisting of five segments each: two end span segments, two pier segments, and one "drop-in" segment; cast-in-place concrete abutments and piers founded on driven 24-in.- and 30-in.-square prestressed concrete piles; cast-in-place concrete and mechanically stabilized earth-retaining walls; cast-in-place concrete deck and barriers with steel railings

**BRIDGE CONSTRUCTION COST:** \$26.7 million (total project)

after splicing. The approach span end segments and the center span drop-in segments were supported by the haunched pier segments during construction prior to post-tensioning.

The bridge has an 8.5-in.-thick, cast-in-place concrete deck. The roadway barriers are 4 ft 6 in. high with concrete bases and a steel railing, and the pedestrian railing for the shared-use path is 4 ft high with a concrete curb section and steel railing.

The project also includes approximately 600 linear ft of retaining walls on the roadway approaches to the bridge. Mechanically stabilized earth walls are used on the east approach and cast-in-place concrete walls on the west approach.

A pedestrian underpass beneath the west approach embankment provides connectivity along the existing riverwalk on the west bank of the Christina River; a set of cast-in-place concrete stairs connects the multimodal path on the bridge and the riverwalk below. The underpass has a cast-in-place concrete frame, about 50 ft long and 45 ft wide, with an arching ceiling, full lighting, and panels for future displays of artwork.



Erection of an end girder segment in span 1 from the working platform. Note the preinstalled strongback at the pier end of the segment and the end block for post-tensioning anchorages at the abutment end of the segment. The end detail of the girders at the abutments was modified at the request of the precaster because, in their experience, the small piece of the top flange that extends beyond the end block has a tendency to crack at the interface. Photo: R.E. Pierson Construction Company.

### Aesthetic Considerations

Given this bridge's prominent location as a focal point within the riverwalk development, the aesthetics of the structures were deemed quite important. As noted, the geometrics of the bridge (low profile, convenient access, and unencumbered views of the downtown skyline) were critical elements in the bridge's siting and design. As the design evolved, other elements were added to enhance the aesthetics. Bridge piers were shaped and contoured. Abutments and retaining walls were developed

in tandem to ensure a coordinated appearance, especially in the transition areas. Concrete surfaces on the piers, abutments, and walls received stone formliner treatments and were stained for maximum, but subtle, effect. The multimodal underpass, stairway, and adjacent walls were all detailed and treated to coordinate with the bridge detailing, presenting a uniform, pleasing appearance.

### Geotechnical Challenges

The site was contaminated with heavy metals, a legacy of past industrial use.



## AESTHETICS COMMENTARY

by Frederick Gottemoeller

In bridge design, seemingly intractable physical or functional constraints are often a blessing in disguise. Satisfying them allows—indeed requires—creative imagination. Often, the result is a distinctive and memorable bridge, like the Christina River Bridge. The designers had to keep the profile low while ensuring the structure would meet navigation requirements and accommodate future increases in sea level. That left a 45 in. window for the girder depth, which was far too shallow to cross the 180-ft main span with conventional precast concrete girders. Designers of steel bridges commonly solve such constraints with continuous haunched girders, but the Delaware Department of Transportation (DelDOT) wanted a low-maintenance concrete bridge.

Therefore, the designer modified standard precast concrete girder sections to provide haunched sections over the piers and then post-tensioned them together with standard drop-in sections to make girders that are continuous for both live and dead loads. This concept doesn't just solve the clearance problem—it also allows the bridge's shape to express the way the forces on it vary over its length, making a graceful structure that is interesting for waterfront users to view. The shape is enhanced by the gentle arch created by the crest vertical curve. The curve is as long as the bridge itself, much longer than what would be required by stopping-sight distance alone.

The project also encourages pedestrian and bicycle travel along the river by providing an

unusually attractive underpass. Users can see all the way through that underpass from each end, and it is as wide as its approach pathways. There is no threat of being hemmed-in or trapped. The light-colored reflective concrete surfaces let daylight reflect far into the underpass and are easily lit at night. Thus, the underpass always looks bright and inviting. Finally, differentially staining the retaining walls' formliner "stones" ensures that they look like and have the same aesthetic impact as the real thing.

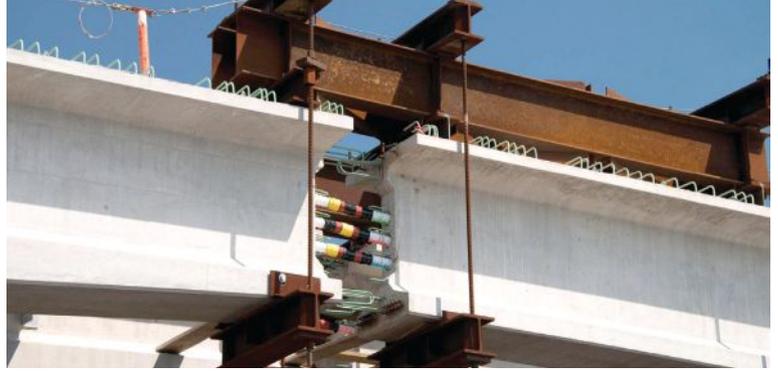
DelDOT's goal for the Christina River Bridge is to catalyze the redevelopment of Wilmington's downtown riverfront in functional, aesthetic, and symbolic terms. I'm confident that visitors to Wilmington 10 years from now will find that the bridge has done exactly that.

### EDITOR'S NOTE

*A special thanks to Fred for this 50th Aesthetics Commentary in ASPIRE.*



With all concrete girder segments erected, strongbacks temporarily support girder segments until closure pours and post-tensioning are completed. Photo: R.E. Pierson Construction Company.



A close-up view of the strongback supporting the end segments on the pier segments before the closure pour. Spliced post-tensioning ducts are visible in the 24-in.-wide joint. Stirrups and other closure pour reinforcement had not yet been installed. Photo: R.E. Pierson Construction Company.

The west approach for the bridge is located over an old buried stream/canal. The subsurface soils consisted of a thin crust of fill underlain by layers of very soft, highly plastic silt and clay with bedrock encountered approximately 100 ft below existing grade. Geotechnical design challenges included global stability, long-term settlement, and down-drag on the bridge foundations.

A variety of structural and geotechnical options were studied during design. The proposed geotechnical treatments included expanded polystyrene and low-density, controlled low-strength material as backfill for the retaining walls along the west approach, soil modification using deep-mixing methods along the east approach adjacent to the bridge, and surcharge and quarantine of the eastern-most portion of the embankment. The contractor eventually proposed using controlled-modulus columns in lieu of deep-mixing methods to save time, and this solution was accepted and incorporated into the structure. The bridge and all structures within the project are founded on driven 24-in.- and 30-in.-square prestressed concrete piles.

## Construction

Bridge design was completed in the fall of 2016, and the bridge project was let for bidding in December. The approach roadway work was omitted from the contract for the bridge portion of the project because of challenges with the right-of-way. Separate contracts allowed the bridge construction to begin while the right-of-way issues were resolved. The timing of the bridge and roadway contracts was coordinated with the intent that both projects would be completed at the same time; however, delays to the roadway contract have caused the overall project completion to extend into 2020.

Bids were opened in January 2017, with a low bid of \$28.4 million compared with the engineer's estimate of \$18.8 million. Design changes and value engineering proposals brought the cost down to approximately \$27 million. Construction began in summer 2017.

In the initial stages of construction, the contractor decided to use temporary work platforms built out into the river adjacent to the bridge end spans. This provided good access for equipment and material supply out to the river, where floating cranes and other equipment would be positioned.

The contractor also decided to install temporary bents within the footprints of the two end spans on the landward side of the two piers. These provided stable platforms to support the precast concrete pier segments until the closure pours and post-tensioning were completed.

Cofferdams were used to build the foundations for the two piers in lieu of floating in formwork boxes. Within the cofferdams, the contractor used precast concrete soffit slabs to serve as a template for the pile driving and as bottom formwork for the pier footings. Finally, the contractor drove two

temporary test piles within the end-span footprint to ensure drivability of the proposed prestressed concrete piles.

The post-tensioned concrete girders are designed as fully continuous for deck dead load, superimposed dead load, and live load. The girder segments were cast using 9000-psi concrete with seven-wire, low-relaxation, 0.6-in.-diameter strands. Minimum compressive strength at transfer was 6800 psi. Each girder had three post-tensioning tendons with twelve 0.6-in.-diameter strands in a 3<sup>3</sup>/<sub>8</sub>-in.-diameter corrugated plastic duct. A tensioning force of 527 kip was specified for each of the three draped tendons in each continuous girder.

The contractor followed the superstructure sequence of construction detailed in the plans for the erection and splicing of the precast concrete girder segments. Once the piers and abutments were completed, pier girder segments were erected at the piers using the previously installed temporary bents for two-point support. These girder segments were temporarily braced while the concrete pier diaphragms were cast and permanent galvanized steel diaphragms were connected.

View of the completed underpass for the shared-use path. Panels for future displays of artwork are visible on the walls of the underpass. Photo: Robert J. Healy.





View of the completed bridge looking east. The piers were enhanced using formliners and staining. Photo: Robert J. Healy.

Next, the end girder segments were erected with strongback connections preinstalled at the pier ends. The strongbacks secured the ends of the girder segments, providing a 24-in.-wide closure pour in which ducts were spliced. Then bracing was installed, and geometry and alignment checks were made.

The midspan drop-in segments were erected next, again with strongbacks preinstalled at both ends. Alignment, grade, and spacing were checked and bracing was installed.

After all superstructure segments had been erected, ducts were spliced and closure pours were cast. When the

closure pours reached the specified compressive strength of 6500 psi, post-tensioning strands were installed and the tendons tensioned in a specified sequence. After acceptance, tendons were grouted and, following a minimum of three days, strongbacks and temporary supports were removed and end diaphragms cast. Upon completion of these items, the bridge deck, barriers, railings, lighting, and all other appurtenances and structures were constructed, including the retaining walls, underpass, and stairway.

### Conclusion

The bridge and adjoining structures are now substantially complete and

are awaiting the completion of the approach roadways. The entire facility is expected to be finished and operational in 2020. 

*Robert J. Healy is director of structures with RK&K in Baltimore, Md. Jason Hastings is the chief of bridges and structures for the Delaware Department of Transportation in Dover.*

### EDITOR'S NOTE

*Delaware is featured in the State article on page 46.*



Marc Basnight Bridge. Photo: HDR



Shasta Viaduct Arch Bridge. Photo: R. Maggenti

## Expanding Design Options with Lightweight Concrete

The Fall 2019 issue of *ASPIRE*<sup>®</sup> included two articles that reported on the use of lightweight concrete for bridges, including a deck and a post-tensioned box girder in a seismic region.

For the Marc Basnight Bridge (see pp. 18-22 of the Fall issue) in coastal North Carolina, the authors reported that lightweight concrete was used "to reduce dead load on the girders, allowing the girders to span longer distances at the same girder spacing. This reduced both the total number of required spans and, more importantly, the total number of bents and foundations, thereby lowering costs substantially." The authors noted that the lightweight concrete deck, which is exposed to extreme coastal conditions, "was not treated differently with regard to durability or corrosion protection; the North Carolina Department of Transportation permitted the use of sand-LWC in the deck without additional corrosion protection provisions."

For the Shasta Viaduct Arch Bridge in northern California (see pp. 32-34 of the Fall issue), the superstructure was initially designed as conventional concrete. When the structure was evaluated following completion of the arch ribs, several modifications were made to the design. The authors stated that "The most significant modification was lowering the dead load on the arch ribs by using lightweight concrete (LWC) instead of normalweight concrete (NWC) in the superstructure box girder including deck, webs, bottom slab, intermediate and abutment diaphragms, and bent caps." The authors also described the development of the lightweight concrete mixture that was successfully pumped to a height of over 100 ft and at rates exceeding 100 yd<sup>3</sup>/hr.

The use of lightweight in different ways in these two projects demonstrates that lightweight concrete is an economical and currently viable material that can be used for a variety of bridge elements.

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21

## HAMILTON FORM CREATES FUNCTION

### CASE STUDY

## ARCHED SOFFIT FOR CURVED BRIDGE BEAM

"The curved beams for this project were critical. Hamilton Form delivered a soffit for the beams that made the casting simple – we supplied the drawings, they did the rest. I'd count on them for any project when the dimensional accuracy and quality of the product are essential."

*Dennis Fink, General Manager, Plant Operations  
Northeast Prestressed Products, LLC*



### The Project:

The original Frederick Avenue Bridge in Baltimore was a two-span concrete arch design built in 1930. In keeping with the historical character of the area, the replacement bridge is a two-span prestressed concrete structure designed to imitate the original bridge.

### The Challenge:

Northeast Prestressed Products, LLC in Cressona Pennsylvania is supplying the precast elements for the project, including 12 arched sections assembled to create 2 arches on each side of bridge replicating the look of the original double arches.

### The Solution:

To cast the beams, Hamilton Form fabricated a soffit that is 44' long and curves to a 52'6" radius. To form the radius, the understructure material was cut with a high-definition plasma cutter to hold tight dimensional tolerances.

### The Results:

Just like the quality of the precast product is dependent on the form it's cast in, the quality of a curved soffit depends on the understructure. The accuracy of the understructure allowed the skin to be easily welded in place. The resulting product is stunning.



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## PROJECT

# AUBURN'S MOORES MILL BRIDGE

by Paul Froede, Alabama  
Department of Transportation



Lee County Road 146, locally named Moores Mill Road, is the southeast arterial into Auburn, Ala., home to Auburn University. The road has crossed over Interstate 85 (I-85) since 1958, when a four-span, 246 ft 10 in. reinforced concrete deck girder bridge was built. That structure had a gutter-to-gutter width of 24 ft 0 in., with no space for pedestrian traffic, and average daily traffic (ADT) was 500 vehicles. ADT is currently over 12,000 vehicles and is expected to increase dramatically because Auburn is the fastest growing city in the state. The lack of a pedestrian crossing and growing vehicular traffic demands led the City of Auburn to initiate a bridge replacement project.

In March 2016, construction began on the new two-span bridge, which is 240 ft 0 in. long with two lanes in each direction, a 14 ft 0 in. bidirectional turn lane, and a 9 ft 1½ in. shared-use path, for a total out-to-out width of 87 ft 9 in. The bridge was constructed with modified 54-in.-deep bulb-tee precast, prestressed concrete girders. A Jersey-type barrier rail separates vehicular traffic from pedestrians and bicycle traffic on the shared-use path.

Precast concrete columns for the Moores Mill Bridge, measuring 3 ft 6 in. by 3 ft 6 in. by 19 ft 9 in., weighed over 18 tons each and were installed on cast-in-place footings using a coupler system with dowels. All Photos and Figures: Alabama Department of Transportation.

### Initial Construction Challenges

Closing the existing bridge to accommodate new construction was not an option, so the new alignment was shifted slightly to the west and the bridge was built in two stages. Stage 1 kept traffic flowing on the old bridge while two lanes and the shared-use path were constructed to the west. Upon completion of stage 1, traffic moved from the old bridge to the completed portion of the new bridge. In stage 2, the old bridge was razed and the remainder of the new bridge built.

Although the abutments are monolithic, the substructure in the median is composed of two distinct bents corresponding to the two stages of construction. Each bent has three columns (six columns total). Originally, the plan was to prefabricate both columns and bent caps. However, high-voltage (more than 700 kV) power lines that had been on the east side of the existing bridge were relocated to the west side of the bridge (stage 1 side) before construction began, placing

them approximately 20 ft from the outside edge of where the new bridge was to be constructed. The location of the power lines and maintenance of traffic constraints on I-85 precluded the use of a crane in the median (the old bridge was on one side of stage 1



Detail of the precast column base with couplers that connect to dowels in the cast-in-place footing.

## profile

### MOORES MILL BRIDGE / AUBURN, ALABAMA

**BRIDGE DESIGN ENGINEER:** Alabama Department of Transportation, Montgomery, Ala.

**PRIME CONTRACTOR:** Scott Bridge Company, Opelika, Ala.

**COLUMN AND GIRDER PRECASTER:** Forterra, Pelham, Ala.—a PCI-certified producer

**ALUMINUM SAFETY RAIL SUPPLIER:** Gatordock Marine Access Solutions, Sanford, Fla.

construction and the power lines were on the other). Therefore, a larger (500-ton) crane positioned behind an abutment would be required to place the precast concrete caps.

When the project was initially bid, the bids were extraordinarily high. This resulted in the project not being let, and Alabama Department of Transportation (ALDOT) engineers revised the bridge design to be more affordable. Among the changes were the precast concrete bent caps, which were eliminated primarily due to their weight and the type of crane necessary to hoist them into place. Because the bent caps were already designed as separate elements and time to revise was at a premium, the caps were not redesigned to become a single element. The bent caps were simply changed from precast concrete to cast-in-place concrete; no changes to the reinforcement design were required. After the project was awarded, the contractor proposed a modification to the maintenance of traffic on I-85; it was approved, allowing a crane to be placed in the median. The revised cast-in-place bent caps were still used.

### Made-to-Order Prefabricated Bridge Elements

ALDOT had joined the accelerated bridge construction (ABC) “club” a couple of years before the Moores Mill Bridge project with a dual-bridge slide-in project

in Dothan, Ala. The Moores Mill Bridge project presented another opportunity to use ABC methods with large, precast concrete bridge elements. ALDOT has maintained standard drawings of prefabricated bridge systems for use on secondary (county and city) road systems, but those elements are light—weighing less than 2 tons per piece. Precast concrete columns for the Moores Mill Bridge, measuring 3 ft 6 in. by 3 ft 6 in. by 19 ft 9 in., were calculated to weigh over 18 tons each.

The columns were cast vertically, primarily due to the formliner on the sides and the desire to achieve a clean, smooth appearance and ensure faux mortar lines were well formed. The precaster used a plywood template to set coupler locations in the column base; that template was later sent to the contractor, who had matching steel templates made for setting dowel bar positions in the cast-in-place footings. Fabrication of the six columns took about three weeks. Notably, casting the last column took much less time than casting the first because the producer became more familiar with the fabrication setup of these unique columns.

The prefabricated column installation took two days: one day to install and one day for the grout to set. Had the columns been cast-in-place, installation would have taken 10 days: two days to

erect three pretied steel reinforcement cages and forms with formliner installed, a day to place concrete, and seven days to achieve sufficient concrete strength before bent cap construction could begin. Thus, eight days of field time per construction stage were saved by prefabricating the concrete columns.

The footings were typical cast-in-place construction, hosting one column each and sitting on nine HP12×53 piles. The steel template based on the bar-coupler positions in the precast concrete columns was used to hold the no. 11 dowel bars in place during concrete placement. It was tack-welded to angle irons to ensure the dowel bars were immobile until after the concrete had cured. The footings were placed and cured according to standard (non-ABC) procedures.

The sequence for installing the columns included the following steps:

1. Keep the footing interface area below the column wet for a minimum of 24 hours.
2. Set shim plates for stability and plumbness.
3. Do a dry-fit test of the column on the footing to ensure proper fit of dowel bars and couplers before preparing the grout bed. Verify shim stack height.
4. Lift the column off the footing, and prepare grout for footing-column interface sealing.

Formliners and staining were used to simulate brick on the Moores Mill Road bridge. Other aesthetic enhancements are the decorative bands on the columns and the chevrons on the bottom surface of the bent caps.



### CITY OF AUBURN, OWNER

**BRIDGE DESCRIPTION:** 240-ft-long, two-span, simply supported prestressed concrete girder bridge

**STRUCTURAL COMPONENTS:** Twenty-four modified BT-54 bulb-tee prestressed concrete girders with a 7-in.-thick cast-in-place concrete deck, six precast concrete columns (each 3 ft 6 in. by 3 ft 6 in. by 19 ft 9 in.), two cast-in-place concrete bent caps, and pile-supported footings and abutments

**BRIDGE CONSTRUCTION COST:** \$3.97 million (\$188.33/ft<sup>2</sup>); \$2.72 million estimated



A steel template based on the bar-coupler locations in the precast concrete columns was used to position the no. 11 dowel bars while placing concrete in the footings.



After a dry-fit test of the column on the footing to ensure proper fit of dowel bars and couplers, the grout bed was prepared for final setting of column. Two rows of ports for grouting couplers are visible at the base of column.

5. Place grout in the defined bed; set the column, and plumb with guywires.
6. Prepare coupler grout according to manufacturer's instructions.
7. Pump grout into the coupler according to manufacturer's instructions.
8. Allow grout to set for 24 hours according to manufacturer's instructions.

### Going All In

Recently, the City of Auburn has been methodically working to provide residents and visitors with a more aesthetically appealing environment, so aesthetics were an important consideration for the Moores Mill Bridge. Designers incorporated aesthetic treatments on many areas of the bridge and tied everything together with a unified weathered-brick look. An 18-in.-high knee wall with a 4 ft 6 in. safety rail on top was constructed for the outside edge of the bridge on the shared-use path side. The line of the railing was broken every 40 ft by a 6-ft-high, 2 ft by 2 ft column to add visual interest. Aluminum was selected for the safety rail to obviate concerns for rust; the rail's heavy, shiny coating of black fluoropolymer is anticipated to last 20 years. Turnback walls at the abutments hide the girder ends and light supports were incorporated into the barrier rails for the decorative streetlights.

The columns and bent caps were included in the aesthetic enhancements and received special consideration. The cap design incorporates visually pleasing sharp angles because no aesthetic formliners were used in the cap construction. The columns have brick formliners at the bottom and a plain concrete finish at the top. These two distinct sections are separated by a 6 in. decorative band. When determining how far up the column the band should be placed, the designers turned to the Fibonacci sequence/golden ratio, situating the shelf at an elevation 61.8% of the height of the installed column above the ground level.

Because there were almost 2100 ft<sup>2</sup> of bridge area to receive the aesthetic brick treatment, formliner was chosen as the most economical way to accomplish this.

For coloring, the contract stated:

Final coloration of the brick concrete surface shall accurately simulate the appearance of the brick in the Auburn welcome sign found at the intersection of Hamilton/Ogletree Roads and Moores Mill Road, including the multiple colors, shades, and flecking that is apparent in real brick.

The contractor was also required to construct and stain a test wall with formliner for practice and coloration approval. On paper, the specification seemed reasonable; however, it did not work out well. After several color schemes were proposed and an additional test wall built and stained, it became apparent that matching the welcome sign was not possible. The colors finally chosen were representative of colors found in other brick structures in the area.

Scuppers or other drainage systems are usually incorporated on bridges of this length. However, placing drains through the deck might lead to stains on the outside girder or the sloped concrete under the bridge. Because the bridge is in a crest vertical curve and the north end is in a horizontal transition, ALDOT engineers widened the roadway to include a 4 ft shoulder to accommodate deck drainage. This

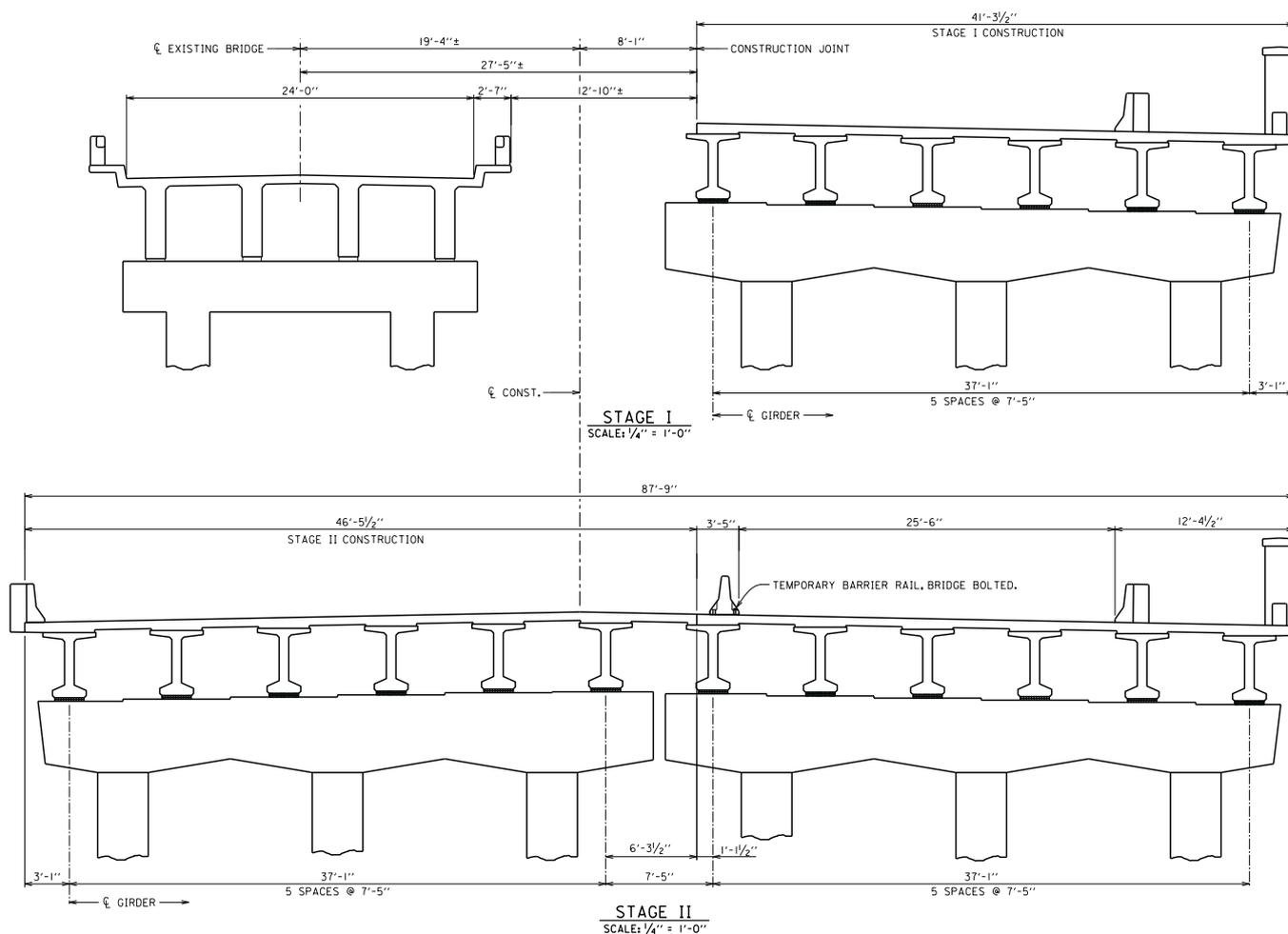


Grout was pumped into the couplers according to manufacturer's instructions, but some locations required a modified approach to address challenges encountered during construction.



These 54-in.-deep bulb-tee precast, prestressed concrete girders, cast-in-place bent cap, and precast concrete columns were erected during stage 1. The brick formliner and decorative band on the column and the chevrons on the bottom surface of the bent cap were aesthetic enhancements.

The completed Moors Mill Bridge provides safe pedestrian and bicycle crossings and increased vehicular capacity for Auburn, Ala., the fastest-growing city in the state.



Typical section of the bridge showing stages 1 and 2 of construction. During stage 1, traffic used the existing bridge while two lanes and the shared-use path were constructed to the west. In stage 2, traffic was moved to the new bridge, the existing bridge was razed, and the remainder of the new bridge was built.

width was determined by hydraulic calculations to be sufficient to prevent rainfall “sheeting” from reaching into the travel lane on the high side. Additionally, sections of PVC pipe were incorporated into the base of the aesthetic columns along the shared-use path to prevent water buildup in that area.

### A Lesson Learned

Although the erection of the precast concrete columns went as expected, the project team encountered an unanticipated event during coupler grout injection. When the columns were unloaded after transportation to the site, they were left in the horizontal orientation to allow for visual inspection and water cleaning of the couplers. When it was time for installation, the contractor lifted and carefully lowered the column onto the footing—the dowel bars into the couplers—as required in the practice fit-up. The column was then lifted to facilitate grout bed preparation, seal

washer installation, and inspection of the dowel bars. There were no instances of damaged bars noted during these inspections, and no sounds of steel-on-steel rubbing or grinding were heard during lowering. However, when the contractor began injecting the grout in the bottom port of some couplers (less than one per column), the grout pump inexplicably stopped, as if a valve had shut, and no additional flow was possible.

The following conditions were observed during these events:

- The affected coupler would allow five pump cycles of grout to flow (it took seven cycles to fill each coupler).
- The issue was not in the pump itself.
- The grout already inserted could be washed out, and water could flow unimpeded through the coupler.
- Running water through the coupler did not improve subsequent grout flow; the pump would stop again after five pump cycles.

- No pattern was observed regarding which dowel bar would experience the problem (location in the bar arrangement, orientation, etc.).

The contractor’s solution to the problem was to move the grout insertion tube to the top port, make two complete pumps and then a partial one, and then move the tube to the bottom port and continue pumping. This technique filled the connector, and workers observed grout flowing out of the top port, as required according to the coupler manufacturer’s installation instructions.

### Conclusion

The bridge was completed within the 270 construction days allowed and opened to traffic in January 2018. Feedback from the public has been overwhelmingly positive. **A**

*Paul E. Froede is the miscellaneous structures and bridge design section supervisor with the Alabama Department of Transportation in Montgomery.*

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## PROJECT

# Two Bridges with a Shared Design

## A proven precast concrete solution increases efficiency on an emergency Kansas City project

by Eric Schrader and  
Brian Zeiger, HDR

Interstate 670 (I-670) is a busy corridor cutting through the heart of downtown Kansas City, Mo., with many downtown streets bridging over the depressed highway. In the last decade, two bridges over I-670, the Main Street Bridge and the Grand Boulevard Bridge, were replaced. Each project had unique goals and challenges: Main Street was chosen as the corridor for the Kansas City Streetcar, and Grand Boulevard was envisioned as a new bike-friendly corridor through downtown. But similarities in the two projects—vicinity, environment, size constraints—allowed project teams to employ solutions already proven on the first bridge replacement to meet an aggressive emergency schedule on the other.

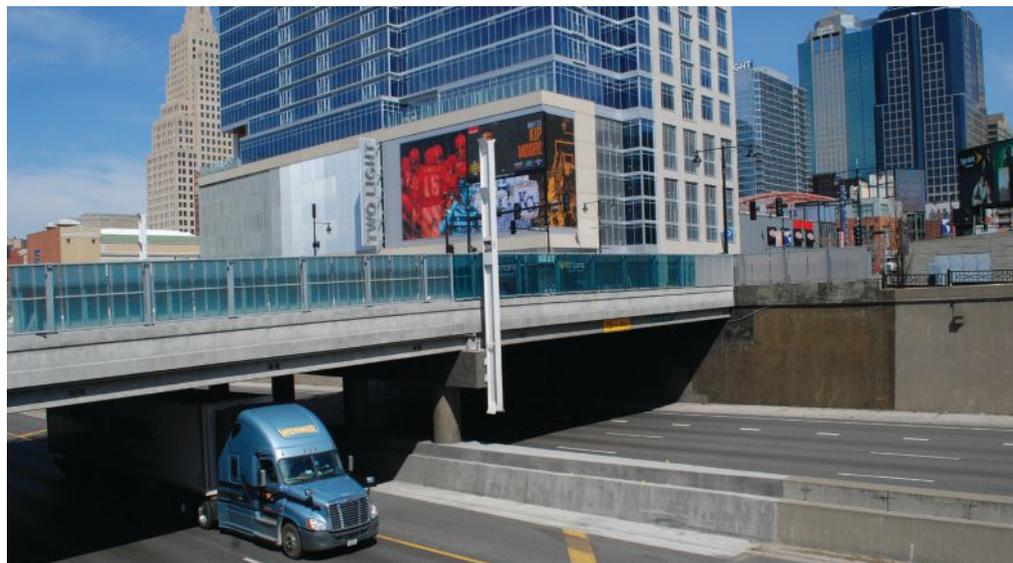
### The Main Street Bridge

The first project, begun in 2012, was the replacement of the Main Street Bridge. It was a fast-paced project requiring close coordination between the City, the Missouri Department of Transportation (MoDOT), numerous local stakeholders, and the team overseeing the Kansas City Streetcar project. The existing bridge was at the end of its useful life, and, with an impending need for a bridge to carry the streetcar, replacement was chosen as the appropriate course of action.

As survey and geotechnical investigations began, the bridge and roadway design



Elevation view of the Main Street Bridge. Note that a streetcar is crossing the bridge. All Photos and Figures: HDR.



Elevation view of the Grand Boulevard Bridge.

## profile

### MAIN STREET AND GRAND BOULEVARD BRIDGES / KANSAS CITY, MISSOURI

**BRIDGE DESIGN ENGINEER:** HDR, Kansas City, Mo.

**PRIME CONTRACTORS:** Pyramid Contractors Inc., Olathe, Kans. (Main Street Bridge); Clarkson Construction Company, Kansas City, Mo. (Grand Boulevard Bridge)

**PRECASTER:** Coreslab Structures, Kansas City, Kans.—a PCI-certified producer



Streetcar rails were embedded in the Main Street Bridge deck. For improved durability, epoxy-coated reinforcement was used in the decks and piers of both bridges.

staff faced their first major challenge: increasing the vertical clearance under the bridge (over I-670) while minimizing profile grade adjustments to Main Street. Any significant raise in profile grade would adversely affect neighboring businesses and intersecting streets. The existing 141 ft, two-span concrete voided-slab bridge had a shallow superstructure depth of 2 ft 3 in. and a 66 ft out-to-out width. The new configuration of Main Street required increasing the out-to-out width by 2 ft, to 68 ft. Like the old bridge, the

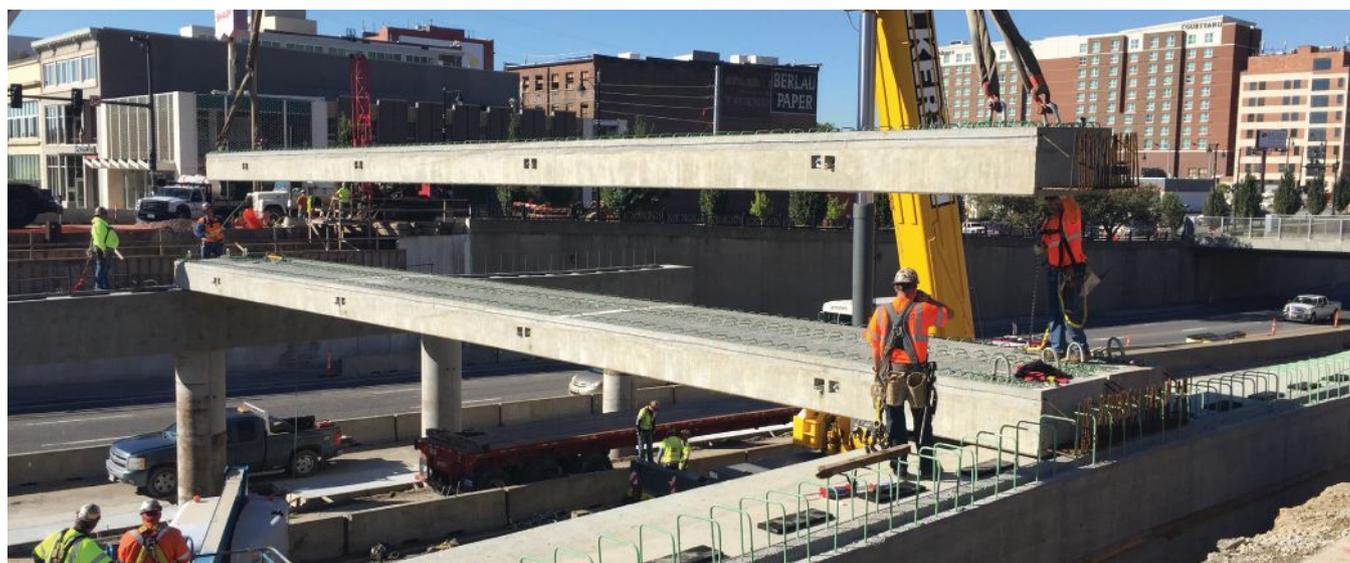
new bridge was designed as a two-span structure, but with a total length of about 148 ft because the design placed the new abutments behind the existing retaining walls and abutments.

Finding the most efficient superstructure type was paramount. After different superstructure types were studied during the preliminary design phase, an adjacent concrete box beam superstructure was determined to be the most efficient structure type that would satisfy the project objectives.

Because the adjacent concrete box beams are shallow with minimal deck thickness, they proved to be the right choice for a replacement superstructure that needed to increase vertical clearance below and widen the roadway on the bridge. The precast, prestressed concrete box beams were also preferable because they were manufactured off site and then quickly installed on site, which minimized traffic impacts to I-670.

The beams chosen were 72-ft-long, 24-in.-deep box beams, either 3 or 4 ft wide, with a 28-day design concrete compressive strength of 8 ksi. The 3-ft-wide box beams had twenty-four 0.6-in.-diameter prestressing strands initially tensioned to 1055 kip, and the 4-ft-wide box beams had 26 strands tensioned to 1143 kip. The beams were designed for both streetcar and highway vehicular live loads. Initially, a minimum deck thickness of 6 in. was chosen for this adjacent box-beam superstructure, but the thickness was later increased to 7.5 in. minimum to provide adequate depth to inlay the new streetcar rails in the deck.

Erection of a 72-ft-long, 2-ft-deep precast, prestressed concrete box beam for the Grand Boulevard Bridge. To facilitate the tight schedule of the emergency bridge replacement, the project team used the same beam design (length and strand layout) and shop drawings as the Main Street Bridge. Note the blockouts for transverse connections between beam units.



## CITY OF KANSAS CITY, MO. (MAIN STREET BRIDGE), MISSOURI DEPARTMENT OF TRANSPORTATION (GRAND BOULEVARD BRIDGE), OWNERS

**BRIDGE DESCRIPTIONS:** Two-span, 148-ft-long bridges using precast, prestressed concrete box beams with cast-in-place concrete multicolumn bents on drilled-shaft foundations. The Main Street Bridge was designed for streetcar traffic as well as other vehicles.

**STRUCTURAL COMPONENTS:** 24-in.-deep precast, prestressed concrete box beams; cast-in-place concrete deck; with epoxy-coated reinforcement cast-in-place concrete bents caps, columns, and drilled shafts



Erection of one span of prestressed concrete box beams for the Grand Boulevard Bridge. The reverse crown in the cross section and pier cap is visible.

A fast-paced schedule was required to replace the bridge before construction of the Kansas City Streetcar project commenced. Final plans were completed and the bid package was prepared to meet the accelerated schedule. The project was under construction by September 2013, with a planned project duration of only 50 days. The new bridge was opened to traffic in December 2013.

### The Grand Boulevard Bridge

Less than three years later, emergency replacement of the existing concrete voided-slab Grand Boulevard Bridge,

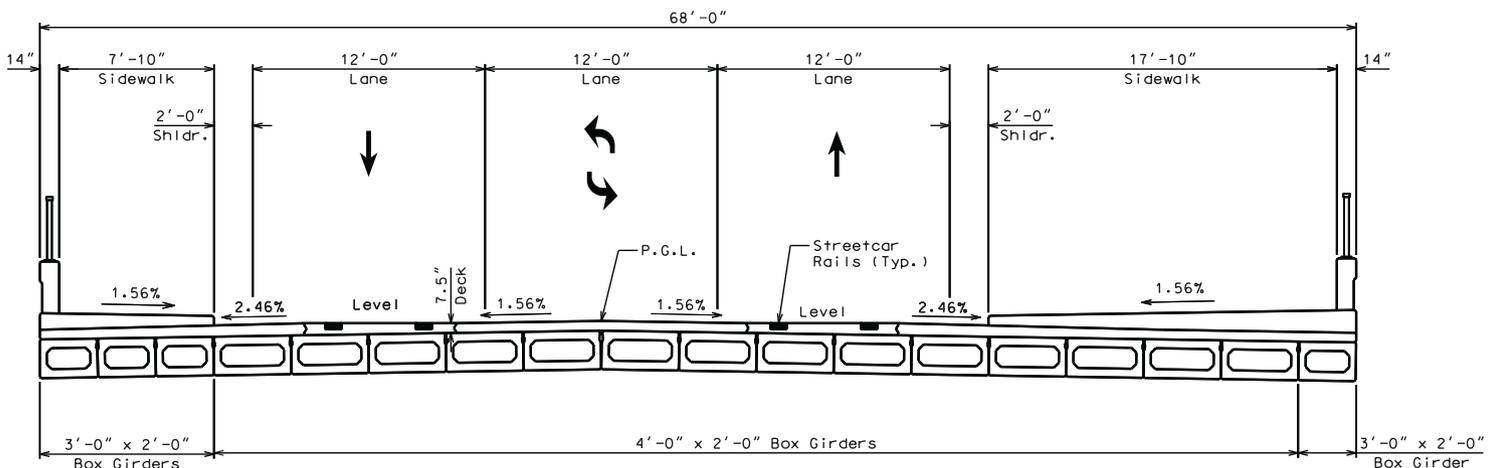
two blocks east of the Main Street Bridge, was deemed necessary after significant cracking was observed in the edge of the slab near the pier. An emergency closure shut down traffic on May 6, 2016, and shoring was installed near the pier under the damaged area. Given the recent success of the nearby Main Street Bridge replacement, the design team for that project was also selected for the replacement of the Grand Boulevard Bridge.

Many of the same challenges encountered on the Main Street Bridge project were faced again on Grand Boulevard, including the need for a wider

bridge and greater vertical clearance below. The out-to-out width of the bridge was being widened from 84 ft to 92 ft 10 in. to accommodate wider sidewalks and a protected bike lane.

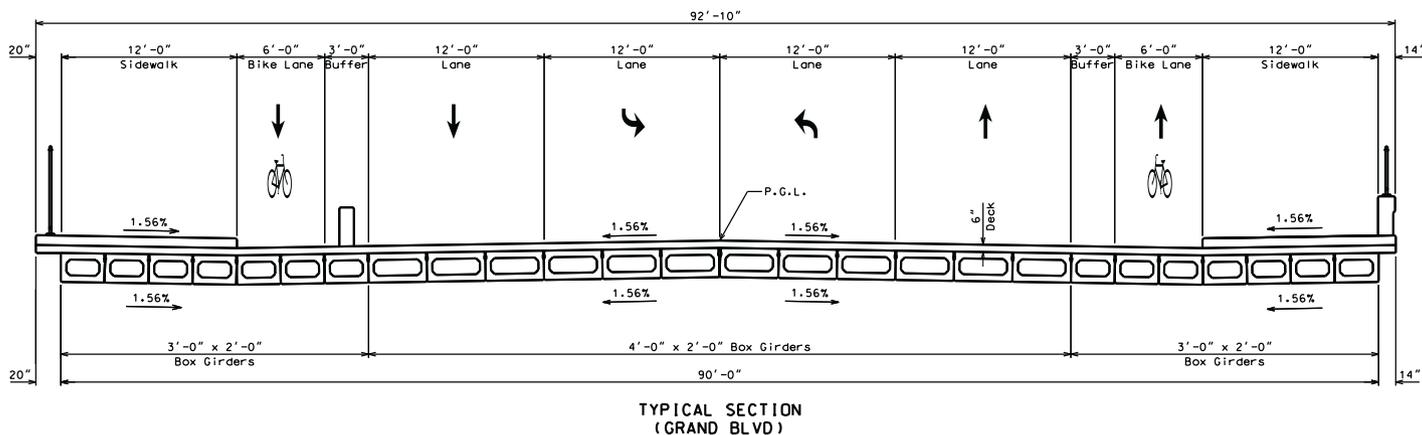
Minimizing the project's impact on intersecting streets and nearby businesses was once again a challenge, but this time the team could draw from what they had learned while meeting these challenges just two blocks away on the Main Street project.

For the Grand Boulevard Bridge, designers proposed using the same two-span design that had been used on Main



TYPICAL SECTION (MAIN ST)

Typical section of the Main Street Bridge showing the different roadway cross-slopes, including level sections at the flush-mounted streetcar rails. The wide right sidewalk provides safe access for pedestrians and cyclists.



Typical section of the Grand Boulevard Bridge. The 12-ft-wide sidewalks and outer four box beams were sloped inward to obtain the minimum required vertical clearance for Interstate 670 below.

Street. By duplicating the earlier project’s dimensions, the design team could reuse the concrete box-beam superstructure design. The Grand Boulevard Bridge used the same 72-ft-long, 24-in.-deep box beams, with an identical design concrete compressive strength and prestressing strand layout and force, as the Main Street Bridge.

Because the configuration was unchanged, MoDOT and the design team agreed to include the previously approved shop drawings from the Main Street Bridge in the contract’s Job Special Provisions to allow the contractor to expedite the beam fabrication process. The project still followed the normal bidding process, but the previously approved shop drawings could be reused at the contractor’s risk to speed up the delivery and construction process. Faced with the time crunch of an emergency replacement on an important city street, this successful strategy was a major time saver.

Because the bridge width was increasing by nearly 9 ft compared with the existing bridge width, the challenge of improving the vertical clearance over I-670 proved to be difficult to resolve. The innovative solution was to provide an opposite cross slope from the normal crown on the roadway under the sidewalks, creating a “gull-wing” design. The new bridge has two, 12-ft-wide raised sidewalks on each edge. The roadway has a normal crown at the centerline of the bridge, but the sidewalks are

sloped to drain toward the gutter on the roadway, creating an inverted crown at the gutter of the roadway. By making the adjacent box beams under the sidewalk match the slope of the sidewalk and matching the inverted crown at the gutter, the bottom of the bridge superstructure was raised for the outer 12 ft of each side of the bridge. This allowed the low point of the superstructure to be pulled in significantly, achieving the desired increase in vertical clearance without raising the profile of Grand Boulevard.

After the design’s completion, plans were submitted to MoDOT in mid-July 2016, two months after the bridge closure. Demolition of the existing bridge began in the last week of August, and the new bridge was opened to traffic in the first week of December 2016.

### Ensuring Durability

The durability of both bridges was an important design consideration. Winters in Kansas City can be harsh, and deicing salts are used to prevent bridges from icing. Epoxy-coated reinforcement was used in the decks to protect the reinforcing bars from corrosion and deterioration due to the effects of moisture and deicing salts.

Because I-670 is depressed and bordered by retaining walls as it passes under Main Street and Grand Boulevard, the highway can create a severe splash zone, which can have a whirling effect from traffic. When deicing salts are applied on the highway

below the bridges, the splashing and whirling of moisture can be detrimental to the long-term durability of the structures. Therefore, epoxy-coated reinforcement was used in the piers as well as the deck. An epoxy protective coating was also applied to the surface of the concrete to protect the piers and retaining walls in front of the abutments for both bridges.

In addition, several details were used to encourage uniform vertical deflection of the box beams to minimize reflective cracking in the cast-in-place concrete deck. The adjacent box beams were connected with a combination of post-tensioned rods and grout-filled keyways. Adjustments for alignment were achieved with a series of wedges placed between the box-beam flanges.

### Conclusion

Precast, prestressed concrete box beams provided the ideal superstructure type for both of these fast-moving bridge replacement projects. The shallow structure depth, the ease of beam placement, and the efficiencies gained by using the same beam design on both projects helped the design and construction teams achieve the objectives of these projects despite the aggressive schedules. It would have been difficult to be as efficient in design and construction with any other superstructure type. **A**

*Eric Schrader is a bridge engineer and Brian Zeiger is a senior bridge engineer in HDR’s Kansas City, Mo., office.*

# Ultra-High-Performance Concrete Optimization of Double-Tee Bridge Beams

by David Gee, Dr. Micheal Asaad, and Dr. Maher K. Tadros, e.construct USA LLC

Ultra-high-performance concrete (UHPC) was first introduced as reactive powder concrete in the early 1990s by employees of the French contractor Bouygues. Since then, France, Japan, and several other countries have made significant progress in using this material for bridge construction and other applications. The first roadway bridge with UHPC beams was built in France in 2001.<sup>1</sup> It was made of five 2-ft-11-in.-deep double-tee (DT) beams (Fig. 1a) and had two equal spans of 72 ft 2 in. each. The beam section had two stems with bottom bulbs to allow placement of prestressing strands and was referred to as a “π-shaped beam.”

In the United States, several state departments of transportation are exploring applications of UHPC for their bridge projects; the use of UHPC for some projects has been supported by the Federal Highway Administration (FHWA) and research performed by local universities. Most notably, Iowa has built several bridges with UHPC components. In 2008, Iowa built a bridge in Buchanan County with a π-shaped beam similar to the French section (Fig. 1b). The bottom bulb of the Iowa bridge was influenced by Massachusetts Institute of Technology<sup>2</sup> and FHWA<sup>3</sup> research (for more

information on this bridge, see the Project article in the Winter 2010 issue of *ASPIRE*<sup>®</sup>). Several companies currently market prepackaged UHPC in the United States. The material has mostly been used in joints between precast concrete members.

To advance UHPC applications in the United States, the Precast/Prestressed Concrete Institute (PCI) has awarded an implementation project led by e.construct, with participation from Wiss, Janney, Elstner Associates; the University of Nebraska-Lincoln; North Carolina State University; and Ohio State University. This ongoing project focuses on assisting six participating precasters in developing their own UHPC mixtures at a lower cost than commercial prepackaged materials, thus enabling development of precast, prestressed concrete bridge and building members at an initial cost competitive with the cost for conventional concrete (CC) members. The research project is scheduled to be completed in 2021. It will include materials and structural design guides with fully worked design examples. So far, the project team has successfully helped all six precasters develop acceptable UHPC mixtures for use in their current production facilities. Also,

preliminary conservative design guidelines have been developed based on published national and international research. After full-scale testing is performed in 2020, these guidelines will be refined to produce additional optimization.

Even when using the proposed preliminary design guidelines for the design of prestressed bridge girders, significant savings in concrete quantities and near elimination of reinforcing bars can be realized.

## Definition of UHPC

There is currently no universally accepted definition of UHPC. Design compressive strengths of UHPC typically range from 17 ksi to 22 ksi. The PCI project defines a minimum compressive strength at transfer of 10 ksi and at service of 18 ksi. While these compressive strengths are higher than the compressive strength of typical concrete used for prestressed girders, the material properties of UHPC that provide the most significant benefit for structural design are the tensile strength and tensile ductility. The steel fibers in UHPC result in these tensile properties being much higher in UHPC than in CC. The PCI project recommends that results from tests of

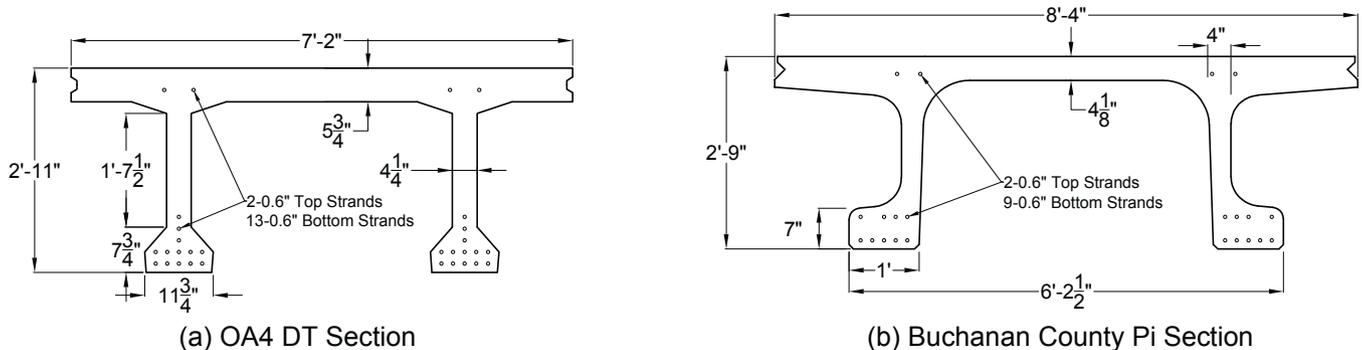


Figure 1. Cross sections for (a) π-shaped beam in France<sup>1</sup> and (b) π section in Buchanan County, Iowa.<sup>2,3</sup> Figure: e.construct.

UHPC performed according to ASTM C1609 *Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete*<sup>4</sup> provide a tensile strength at first cracking of at least 1.5 ksi and peak tensile strength of at least 2 ksi with significant deflection (ductility) beyond cracking (Fig. 2). This high tensile strength allows for much higher shear resistance and the possibility of total elimination of stirrups. The flexural (tensile) strength of fiber-reinforced concrete prisms determined according to ASTM C1609 can be correlated to shear (diagonal tensile) strength. The fibers essentially act as randomly oriented tensile elements crossing the potential diagonal cracks, and this enhances the diagonal tensile capacity.

A typical mixture for 1 yd<sup>3</sup> of UHPC consists of 1200 lb of cement, 150 lb of silica fume, 570 lb of slag (or another supplementary cementitious material), and 1640 lb of fine sand, as well as water-reducing and workability admixtures. The water-to-binder ratio is about 0.18. Fibers are added at 2% by volume, or about 265 lb/yd<sup>3</sup>. The estimated material cost of this mixture would be about \$650 to \$800/yd<sup>3</sup>, which compares favorably to the \$2000 to \$3000/yd<sup>3</sup> cost of commercial prepackaged mixtures.

### UHPC Criteria and Structural Design Guidelines

In the authors' professional opinion, the published literature and other countries' codes provide sufficient knowledge to conservatively perform UHPC beam design until refinements are developed and guide specifications are published. For a prestressed UHPC beam element, flexural design is quite similar to design with CC. The contribution of the steel fibers in UHPC to a beam's flexural strength

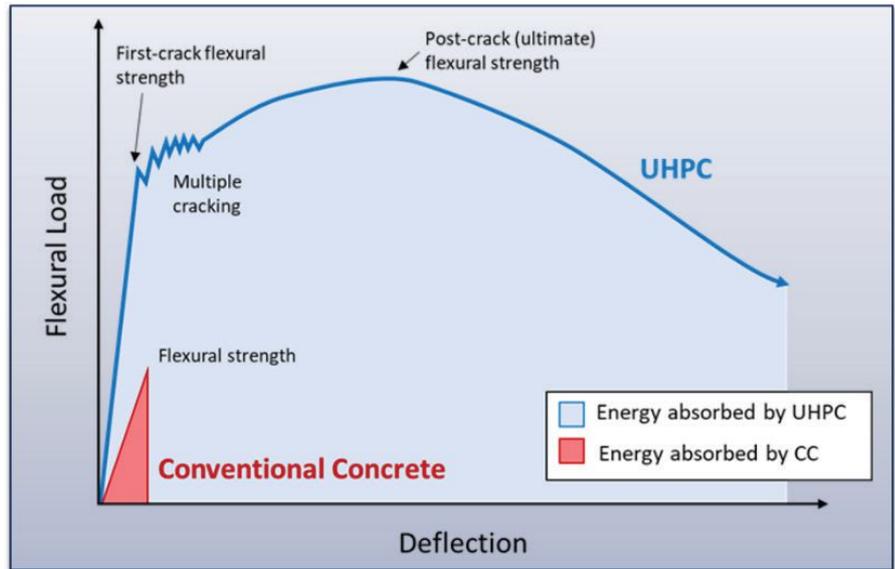


Figure 2. The schematic comparison test results according to ASTM C1609 *Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete*<sup>4</sup> shows much higher tensile strengths and greater ductility for ultra-high-performance concrete (UHPC) than for conventional concrete (CC). Figure: e.construct.

is minimal compared to the resistance provided by the prestressing strands. A major benefit of using UHPC is its shear resistance. It is conservative to assume that UHPC with steel fibers has a nominal shear resistance equivalent to about 0.75 ksi. The 0.75-ksi shear resistance is a conservative design value for UHPC mixtures that meet the following minimum flexural performance requirements as determined using ASTM C1609:

- A tensile strength of 1.5 ksi at first cracking;
- a tensile strength of 2 ksi at peak load;
- a peak load  $\geq$  125% of first-cracking load;
- a tensile stress at  $L/300$  deflection  $\geq$  90% of stress at first cracking; and
- a tensile stress at  $L/150$  deflection  $\geq$  75% of stress at first cracking,

where  $L$  is the span length of the specimen being tested.

Multiple structural benefits are realized when these minimum UHPC requirements are met for prestressed UHPC elements. First, because shear resistance of CC is typically on the order of 0.10 ksi to 0.40 ksi, and the shear resistance provided by stirrups is about the same, stirrups may not be necessary in beams using UHPC. Second, end-zone bursting cracks in pretensioned elements are better controlled with UHPC due to the presence of fibers. Finally, long-term camber growth is virtually nonexistent in UHPC beams because creep is a fraction of that in CC, especially when UHPC-specific thermal curing is introduced (heating to 194°F at 100% humidity for 48 hours within 14 days of transfer).

### Examples of Current Conventional Concrete Double Tees

Bridge DTs have been in use for several decades. They are distinguished from

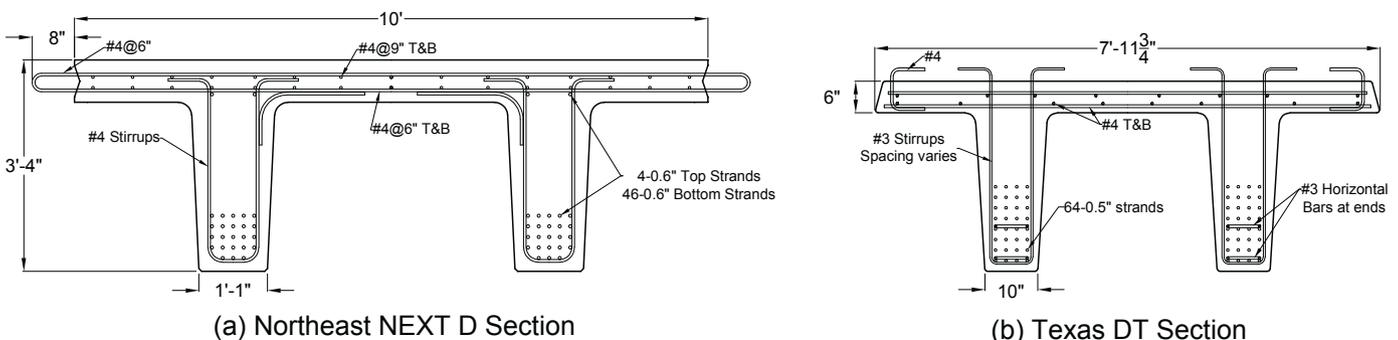


Figure 3. Standard sections for (a) NEXT D and (b) Texas double-tee beams. Figure: PCI Northeast and Texas Department of Transportation.

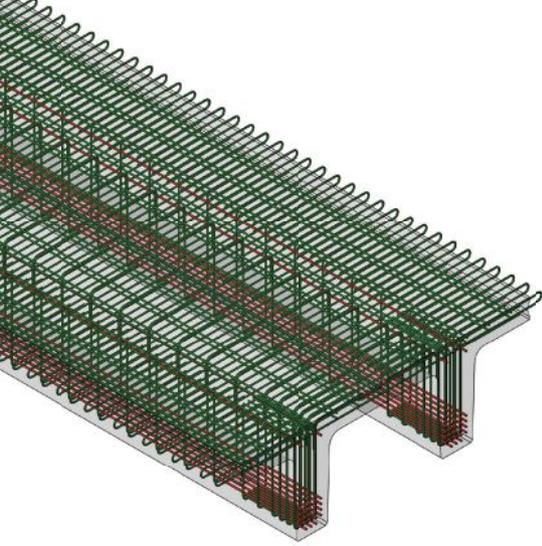


Figure 4. Isometric view of the end of a typical NEXT D beam designed using conventional concrete. Reinforcing bars and prestressing strands are shown. Figure: e.construct.

building DTs, often used in parking structures, by relatively wide stems and a relatively thick top flange. The primary advantage of bridge DTs is ease of fabrication—self-stressing forms, which have no moving parts, can be used. The DTs are stable and require no bracing during handling, storage, and erection. However, a bridge DT may weigh as much as 1 ton per foot of length, possibly creating significant handling, transportation, and erection challenges.

The Northeast Extreme Tee (NEXT) D beam developed by PCI Northeast<sup>5</sup> and a DT that has been used in Texas (Fig. 3) are the focus of the comparison featured later in this article. (Note: The Texas DT section has been archived and details cannot be accessed online.) The two sections shown in the figure represent the deepest and widest products for each type of DT.

The NEXT D beam can accommodate 46 bottom strands and 4 top strands—all 0.6 in. diameter. The NEXT D beam has an 8-in.-thick top flange, which can vary

in width from about 8 to 10 ft and may be covered with a 2- to 3-in.-thick asphalt overlay. The beam weight for a 10-ft-wide and 40-in.-deep section is 1936 lb/ft. With a concrete compressive strength  $f'_c$  of 10 ksi, the span capacity of the 40-in.-deep NEXT D beam is 80 ft. This maximum span can be increased somewhat with more strand debonding at the ends than the customary 25% to 35% limit. For the 80 ft span, thirty-eight 0.6-in.-diameter strands are required in the bottom and the total piece weight is over 77 tons. Figure 4 offers an isometric view of the end of a NEXT D beam designed using CC with reinforcing bars and prestressing strands shown. Note the quantity of reinforcing bars in the beam.

The cross-sectional area of the Texas DT is 1283 in.<sup>2</sup> and the weight is 1336 lb/ft for an 8 ft width. For this analysis, a maximum of eight 8-strand rows, for a total of sixty-four 0.5-in.-diameter strands, are used. The midspan section is the focus of the study with the assumption that, as allowed in Texas, adequate strand draping and/or debonding is provided to satisfy stress limits at the member ends. The Texas DT shape has a 6-in.-thick top flange, which may be topped with a 5-in.-thick composite cast-in-place concrete topping. It may also be covered with a 2-in.-thick noncomposite wearing overlay for secondary road applications. In this example, the composite system is used. With a 10-ksi concrete compressive design strength and a 5-ksi topping, the span capacity of the CC beam is 85 ft. The precast concrete beam weight is 57 tons. Note that the assumed live load distribution factor is 0.7 for the Texas beam and 1.0 for the NEXT D beam; the difference in these factors is due to the different top flange widths.

## Optimized Double-Tee Beams Using UHPC

For each of the two types of DT beams discussed above, an optimized UHPC section was developed. The optimized design was developed so that the current DT beam forms can be used. This is accomplished by inserting blockouts in the existing forms to create a bulb-tee shape in each stem. The resulting sections are similar to the previously described  $\pi$ -shaped beams used in France and Iowa, except that the top flange is also optimized using a ribbed slab. Figure 5 shows the optimized section shapes using blockouts (hatched area) placed within the standard forms. The blockouts would be removed after the product is stripped from the forms. Figure 6 provides an isometric view of the optimized NEXT D beam designed using UHPC. Note the significant reduction in reinforcing bars compared to the section with a CC design in Fig. 4. Figure 7 is an isometric view from below the beam that shows the ribbed deck of the optimized NEXT D beam. The corresponding shape for the Texas beam is similar but is not shown here.

Three sample analyses were performed on the NEXT D beam:

- A CC beam with the dimensions shown in Fig. 3a, an 80-ft span and 38 bottom strands, with the top tensile stress at transfer at the ends limited to 0.20 ksi to eliminate potential cracking of the top face of the member;
- a UHPC beam with the dimensions as shown in Fig. 5a, an 80-ft span to match the CC beam span capacity, and a strand pattern with 30 bottom strands and 12 top strands; and
- a UHPC beam with the dimensions and prestressing strands as shown in Fig. 5a and a 90-ft span.

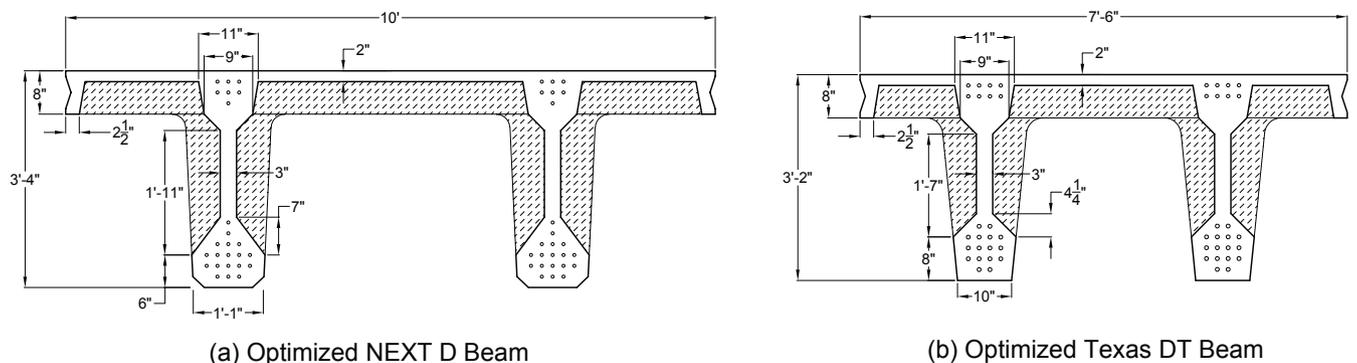


Figure 5. Optimized UHPC shapes for (a) NEXT D beam and (b) Texas double-tee beam based on standard beam shapes with form blockouts. These optimized UHPC illustrative shapes use about 50%–60% of the conventional concrete volume. Figure: e.construct.

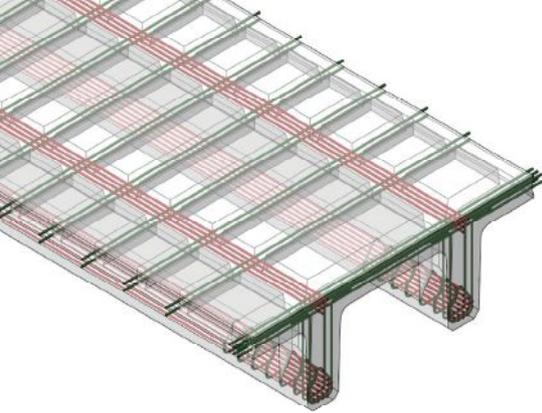


Figure 6. Isometric view of the end of the optimized UHPC twin-stemmed beam from above. Reinforcing bars and prestressing strands are shown. Figure: e.construct.

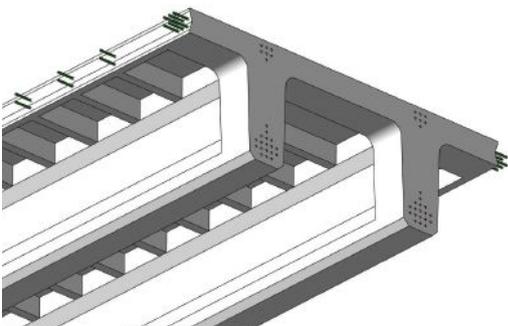


Figure 7. Isometric view of the end of the optimized UHPC twin-stemmed beam from below showing the ribbed deck and solid end block. Figure: e.construct.

Table 1 summarizes the input and output for the three cases. As shown, it is possible to reduce the weight per unit length by about 50% when UHPC is used. The 80-ft-span CC piece weighs about 77 tons, whereas the 80-ft-span UHPC piece weighs about 37 tons, which is 48% of the CC beam weight; a 90-ft-span UHPC piece weighs about 41 tons. Table 1 illustrates that adding more 0.6-in.-diameter strands to the UHPC design can result in a 10 ft increase in the possible span length. A design span of nearly 100 ft can be achieved with 0.7-in.-diameter strands (results not shown in table), which the authors recommend to obtain the greatest value from using UHPC. However, deflections and vibrations become more critical with relatively large span-to-depth ratios. Please note that in all three cases, the beam spacing and beam width are taken to be the same to simplify the comparison.

The absence of reinforcing bars, as allowed by the UHPC design, significantly reduces labor costs in design, detailing, production, and inspection. The authors' analysis for these beams shows no need for bursting or bottom-flange confinement reinforcement. However, a nominal amount is recommended as

a conservative measure until further research shows whether reinforcement can be totally eliminated without objectionable cracking.

If UHPC and no. 6 reinforcing bars or smaller are used in the top flange ribs in the transverse direction, the longitudinal joint between beams can be as narrow as 6 in. This detail follows the FHWA recommendations<sup>6</sup> that a bar development length in UHPC can be as short as 8 bar diameters. Please note that the number of bottom strands in the UHPC beam is less than that for a CC beam of the same span. However, it may be desirable to place more strands in the top, primarily to limit camber.

A similar study was performed on the Texas DT, but the results are not listed in the table. The Texas DT shape, modified as shown in Fig. 5b, was analyzed without a composite cast-in-place topping but with a 3-in.-thick noncomposite asphalt overlay and compared to the 85-ft span Texas DT beam using CC and the composite topping previously described. Using the same concrete properties as the UHPC twin-

Table 2. Comparison of CC and UHPC Beam properties

Section	Area, in. <sup>2</sup>	$I_x$ , in. <sup>4</sup>	$y_c$ , in.
NEXT D CC	1,882	260,900	26.5
NEXT D UHPC	789	170,600	24.4
Texas DT CC	1,280	147,800	23.4
Texas DT UHPC	690	128,700	22.8

stemmed beam example in Table 1, the Texas DT UHPC member can span 95 ft with thirty-two 0.7-in.-diameter bottom strands and sixteen 0.7-in.-diameter top strands. No draping or debonding is required. The weight of the optimized beam is reduced to 795 lb/ft (38 tons), which is 40% lighter than the CC beam used for comparison; this reduced weight does not include the additional reduction from using an asphalt wearing surface instead of a composite cast-in-place topping.

Details at the ends of the UHPC DT beams will need investigation, especially if the end is skewed. A short length at the ends of the DT beams may be made with an 8 in. full-thickness top flange.

Table 1. Comparison of NEXT D Beam designed with CC and the optimized UHPC twin-stemmed beam designs

Parameters	CC beam, 80-ft span	UHPC beam, 80-ft span	UHPC beam, 90-ft span
Concrete compressive strength at transfer (ksi)	8	10	10
Concrete compressive strength at service (ksi)	10	18	18
Specified peak tensile strength (ksi)*	—	2	2
Flange width (ft)	10	10	10
Member depth (in.)	40	40	40
Unit weight of concrete (lb/ft <sup>3</sup> )	150	155	155
Beam weight (lb/ft)	1936	920	920
Number of bottom 0.6-in.-diameter strands (both webs)	38	30	36
Number of top 0.6-in.-diameter strands (both webs)	4	12	14
Total number of 0.6-in.-diameter strands	42	42	50
Design span (ft)	80	80	90
Bottom-fiber tensile stress limit at Service III (ksi)	0.60	1.00	1.00
Computed bottom-fiber tensile stress at Service III (ksi)	0.44	0.94	1.00
Moment demand at Strength I (ft-kip)	6110	5305	6064
Moment capacity (ft-kip)	6174	5389	6074
Shear strength demand at Strength I at critical section (kip)	294	249	258
Design shear capacity at critical section (kip)	520 <sup>†</sup>	362 <sup>‡</sup>	362 <sup>‡</sup>
Estimated camber at midspan at transfer (in.)	1.18	1.26	1.93
Live load deflection at midspan (in.)	-0.70	-0.89	-1.00

\*Peak tensile strength as determined using ASTM C1609.<sup>4</sup> Not required for CC design.

<sup>†</sup>With two legs of no. 4 shear stirrup reinforcement in each stem spaced at 12 in. on center for beams with straight strands.

<sup>‡</sup>With no shear stirrup reinforcement.

This solid top flange could also be useful if there is a desire to make beams continuous for live load because it allows placement of longitudinal continuity bars at the piers.

## Cost Estimates

An approximate cost analysis was performed for the NEXT D beam example. Results would be similar for the Texas beam. The CC beam weighs 1936 lb/ft, corresponding to a volume of concrete of 0.48 yd<sup>3</sup>/ft. The corresponding values for the UHPC beam are 920 lb/ft and 0.20 yd<sup>3</sup>/ft. Assuming an average cost per cubic yard of the 10-ksi concrete is \$150, and cost of shear reinforcement, strands, equipment, labor, and other expenses is \$600, the total product cost becomes \$750/yd<sup>3</sup>, or \$360 per foot of beam for the CC beam. If using UHPC increases the cost of concrete from \$150 to \$800, and the other costs are the same, the total cost becomes \$1,400/yd<sup>3</sup>, but only \$280 per foot of beam for the UHPC beam, resulting in overall savings. Note that actual savings associated with UHPC could be even greater when one considers additional benefits, such as not having

to design, detail, purchase, place, and inspect the shear reinforcement required in the CC beam, or the additional benefits associated with lighter beam weight such as shipping, handling, and foundation design. This analysis is approximate. Unit costs vary significantly from one area of the United States to another.

## Conclusion

The analysis presented in this article shows that, based on the initial findings of the PCI-funded UHPC implementation project, it is possible to have a cost-effective UHPC alternative to the popular DT beams, whose primary drawback is their heavy weights, which may limit span capacities. For the same depth and amount of prestressing force, one can realize a longer span with a significantly reduced weight and near elimination of reinforcing bars. The authors believe that the UHPC option is cost-competitive on a first-cost basis and is much more valuable than the CC design when life-cycle costs are compared. UHPC, with its extremely low permeability and excellent durability properties, is expected to significantly extend the service life of bridges.

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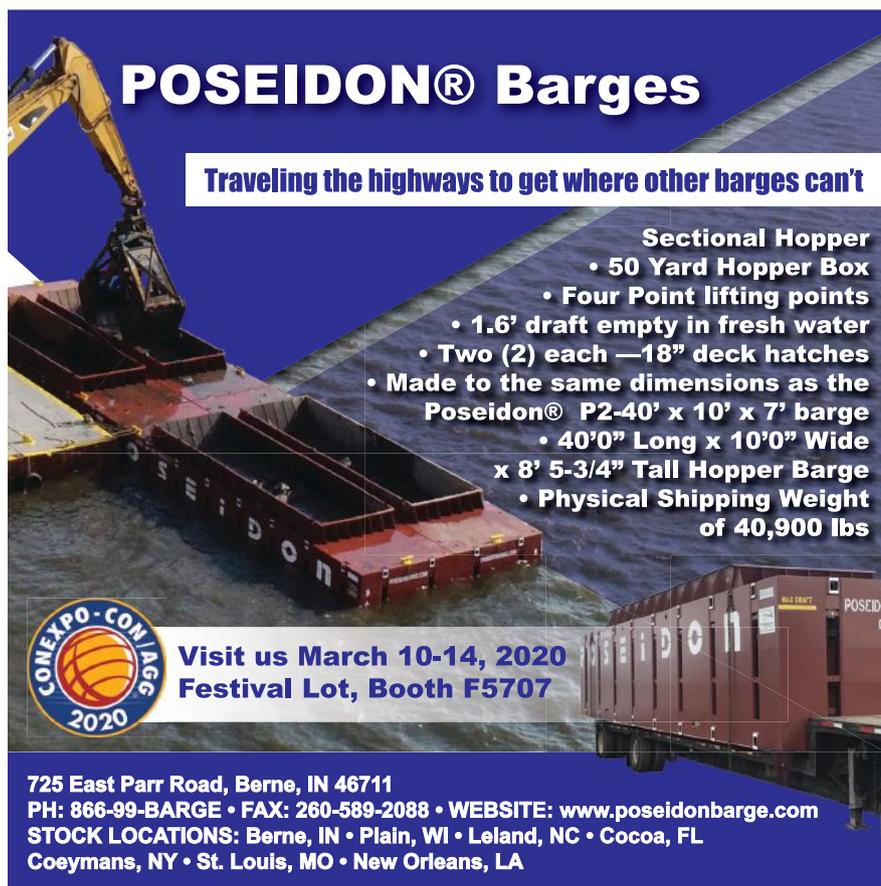
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## EDITOR'S NOTES

See Resources tab on the ASPIRE website for additional information concerning these engineering computations.

See the *Concrete Bridge Technology* article in the Spring 2017 issue of ASPIRE for more information on the use of UHPC for precast concrete bridge girders in Malaysia, which sparked great interest in realizing the potential benefits of UHPC in the United States.



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# What Technologies Are in the Kaleidoscope?

by Dr. Henry G. Russell, Henry G. Russell Inc.

In the editorial for the Fall 2019 issue of *ASPIRE*<sup>®</sup>, William Nickas, Editor-in-Chief, looked into his kaleidoscope and saw many technologies available for today's bridge engineers. This article expands on that vision by arranging some of the pieces to form strategies to enhance the durability and lengthen the service lives of concrete bridges.

To achieve a long service life for concrete bridges, a primary focus of bridge owners and designers is preventing corrosion of nonprestressed and prestressed reinforcement caused by chloride penetration. Because the use of deicing salts in the northern states is unlikely to end in the near future, and bridges will continue to be built in coastal regions, we must live with the presence of chlorides and deal with them accordingly. This article describes three strategies that may be implemented individually or in combination to achieve a longer service life for concrete bridges.

### Strategy A: Improve Chloride Resistance of Concrete

This strategy involves methods to prevent chloride ions from reaching steel reinforcement by sealing the surface or reducing the permeability of concrete, thus minimizing cracking. Because concrete cover is the first line of defense against chloride penetration, reduced chloride penetration is essential. It can be achieved by using any of the following materials:

- Surface sealers
- Penetrating sealers
- Fly ash or pozzolan (Type N)
- Silica fume
- Slag cement
- Water-reducing admixtures
- Corrosion inhibitors
- Shrinkage-reducing admixtures
- Expansive cement or components
- Lightweight concrete

- Ultra-high-performance concrete (UHPC)

Although these technologies have been around for many years, some have never been fully accepted. Surface sealers are intended to prevent or decrease the penetration of water and chlorides into concrete. However, surface sealers have a limited life, often require reapplication, and are not recommended for continuously submerged surfaces. Penetrating sealers enter the concrete and react chemically with the cement hydration products to form a barrier to the penetration of chlorides. They are not effective if the concrete already has a low permeability. The use of fly ash and other pozzolans, silica fume, and slag cement reduces the permeability of concrete, which slows the penetration rate of chlorides.

Water-reducing admixtures are often included in concrete mixtures for other reasons, but they also reduce permeability. These admixtures may also be used to enhance compressive-strength gain or to achieve a higher design compressive strength. A corrosion inhibitor is an admixture that either delays initiation of corrosion or reduces the corrosion rate once corrosion begins.

The use of supplemental cementitious materials or admixtures can reduce concrete permeability in uncracked concrete, but their effectiveness is reduced when cracks are present. A shrinkage-reducing admixture can reduce cracking caused by restrained shrinkage. Some owners have found that expansive cements or expansive components can be used to produce shrinkage-compensating concrete and effectively reduce cracking in bridge decks. Lightweight concrete and lightweight aggregate used for internal curing have also been shown to reduce cracking and permeability.

Finally, UHPC has a negligible permeability. The high steel fiber content of UHPC controls any cracks that may form. Its use is becoming more cost-effective as mixtures using local materials are being developed. (See the Concrete Bridge Technology article on UHPC on page 32 in this issue of *ASPIRE*.)

### Strategy B: Protect Conventional Steel Reinforcement

This strategy involves providing a protective coating around individual conventional steel reinforcing bars or strands to improve corrosion resistance compared with that of uncoated steel reinforcement. Several options are available:

- Epoxy-coated nonprestressed reinforcement
- Stainless steel clad nonprestressed reinforcement
- Zinc-coated (galvanized) nonprestressed reinforcement
- Epoxy-coated seven-wire prestressing strand
- Zinc-coated seven-wire prestressing strand

Coating selection should be based on the application, availability, and cost. Epoxy-coated nonprestressed reinforcement has been available for many years. It is the most frequently used and least-expensive method to protect steel reinforcement, and it will likely be used for many years to come. Reinforcement with stainless steel or zinc coatings are also available, but their use has been limited.

Epoxy-coated steel strands for use in concrete have an exterior coating, and the interstices between wires are completely filled with epoxy so that each wire is individually protected. The epoxy coating is different from that used for

nonprestressed reinforcement because the epoxy must be capable of sustaining large elongations associated with tensioning strands. There are three types of surface finish available for epoxy-coated strands: smooth finish, coarse-grit finish, and fine-grit finish. The purpose of the grit is to provide greater bond than a smooth epoxy coating would provide.

In zinc-coated seven-wire prestressing strands, the individual wires are coated before stranding.

### Strategy C: Use Corrosion-Resistant Reinforcement

This strategy avoids the problem of corrosion by using any of the following types of corrosion-resistant reinforcement:

- Low-carbon chromium steel
- Stainless steel nonprestressed reinforcement
- Stainless steel seven-wire strand
- Carbon-fiber-reinforced polymer (CFRP) nonprestressed reinforcement

#### Comparison of steel strands after exposure to salt spray (fog)<sup>3</sup>



Bare strand after 1000 hours. Photo: Sumiden Wire.



Galvanized strand after 1000 hours. Photo: Sumiden Wire.



Epoxy-coated strand after 1000 hours. Photo: Sumiden Wire.



Epoxy-coated strand after 3000 hours. Photo: Sumiden Wire and CTL Group.



Stainless steel strand after 3000 hours. Photo: Sumiden Wire and CTL Group.

- Glass-fiber-reinforced polymer (GFRP) nonprestressed reinforcement
- CFRP prestressing strand and bar

The selection of the appropriate material should be based on the application, availability, and cost. The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*<sup>1</sup> and *AASHTO LRFD Bridge Construction Specifications*<sup>2</sup> currently allow the use of low-carbon chromium steel reinforcement in bridges in Seismic Zone 1 and the use of stainless steel nonprestressed reinforcement in all zones. Currently, there is not an active material specification for stainless steel seven-wire strand, but ASTM is developing one, which may become available in 2020. The National Cooperative Highway Research Program (NCHRP) has asked for proposals for a project beginning in 2020 to develop design recommendations for stainless steel strand in prestressed concrete bridge elements. This should remove a current barrier to its usage. Notably, the use of stainless steel strand has been demonstrated in at least 15 projects in the United States, primarily in prestressed concrete piles. (See the Concrete Bridge Technology article in the Spring 2018 issue of *ASPIRE*.)

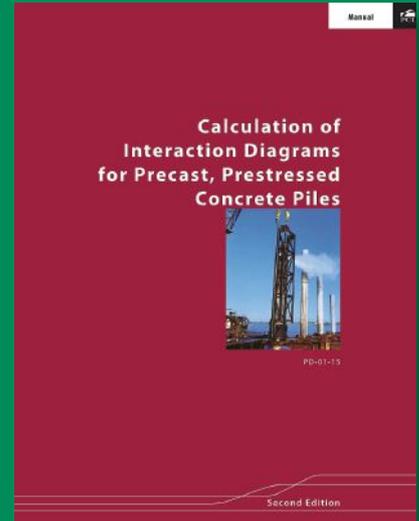
CFRP and GFRP nonprestressed reinforcements have been available for several years, but they have not been used extensively. The use of GFRP nonprestressed reinforcement is addressed in a recently updated AASHTO publication, *AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete*.<sup>4</sup>

The use of CFRP strands and bars is addressed in a recent AASHTO publication, *Guide Specifications for the Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems*,<sup>5</sup> and NCHRP Report 907, *Design of Concrete Bridge Beams Prestressed with CFRP Systems*.<sup>6</sup>

### Closing Remarks

In the future, service-life design for major bridges is likely to receive greater attention as life-cycle costs become a more important consideration. More information about service-life design will be available in an upcoming NCHRP web-

## The Second Edition of



This free eBook, *Calculation of Interaction Diagrams for Precast, Prestressed Concrete Piles*, provides context and instructions for the use of the 2015 revised version of the Micro-soft Excel workbook to compute pile stresses, plot interaction diagrams, and compute lifting points of precast concrete piles.

There is no cost for downloading *Calculation of Interaction Diagrams for Precast, Prestressed Concrete Piles* or the 2015 workbook. However, registration is required so that users can be contacted when updates or revisions to the workbook are necessary.

The Appendix of *Calculation of Interaction Diagrams for Precast, Prestressed Concrete Piles* contains detailed instructions and solved examples using the 2015 workbook. Examples are also solved using Mathcad to validate the workbook solution, and a table of results compares the two methods.

Download the free publication *Calculation of Interaction Diagrams for Precast, Prestressed Concrete Piles* to your computer from [www.pci.org/epubs](http://www.pci.org/epubs).



Precast/Prestressed Concrete Institute  
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only report titled *Guide Specification for Service Life Design of Highway Bridges*.<sup>7</sup>

However, the improvements to service-life predictions offered by the different strategies and materials discussed above remain difficult to quantify.

In construction, the acceptance of new technologies such as CFRP tends to be a slow process because construction is a risk-averse industry. Consequently, steel reinforcement is likely to remain the prominent reinforcement method for many years.

The appropriateness of the strategies described in this article depends on the exposure condition of the bridge components, the components' importance, and the structure's expected service life. These strategies may not be applicable to all bridges, and their use may be limited or mandated by the owner's specifications.

While these technologies can extend the service life of concrete bridges, they increase initial costs. To use a common expression, there is no free lunch.

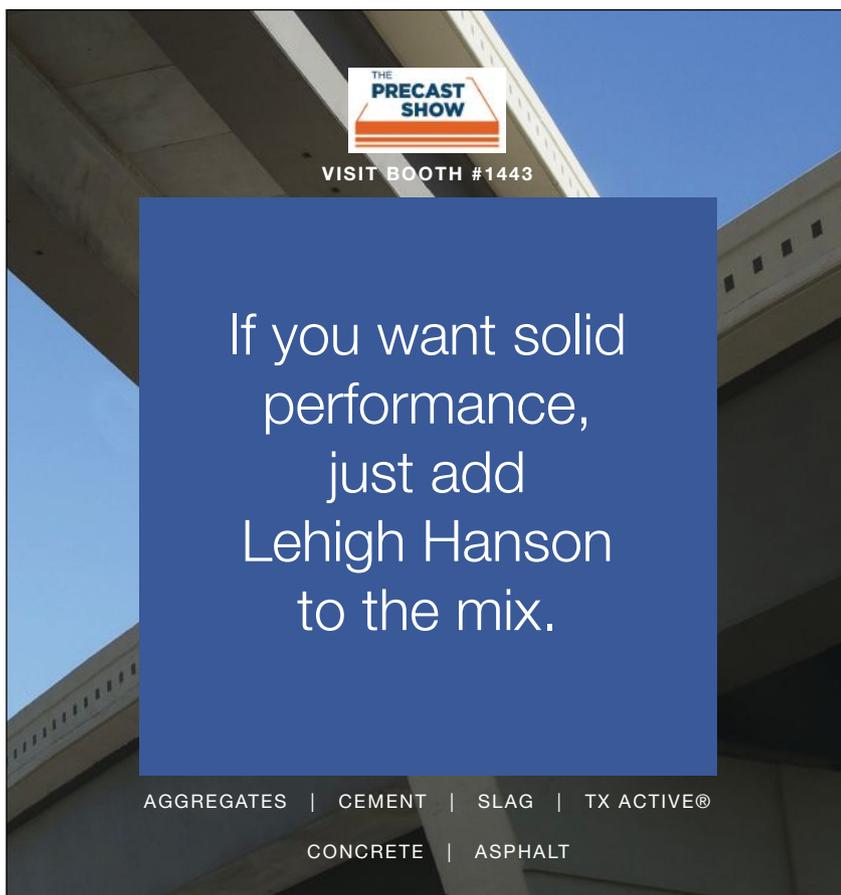
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*Dr. Henry G. Russell is an engineering consultant. He has been involved with applications of concrete for bridges for over 45 years and has published many papers on the applications of high-performance concrete.*



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*\*These PCI eLearning Courses will be available soon.*

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# Equipping Engineers to Deal with the Existing Bridge Inventory

by Dr. Oguzhan Bayrak, University of Texas at Austin

**W**hile some historic U.S. bridges date to the late 19th or early 20th century, most of the highway infrastructure was designed and built after the conclusion of World War II. Since the Federal Highway Act of 1956 authorized the interstate highway system, billions of dollars have been invested in the construction and ongoing expansion of that system. Currently, our aging transportation infrastructure is a cause for concern for all of us. In this article, I share a few thoughts about the challenges we face from the perspective of an educator.

To provide context, let us envision a junior engineer with a few years of experience working for a state department of transportation or a firm in the bridge industry. Many of the problems this engineer will face will be related to the condition of the existing bridge inventory, including structures designed and built by earlier generations of engineers and contractors working under different circumstances. This engineer, as part of a group of engineers or as an individual, will likely be tasked with evaluating a bridge that may be showing its age. We all know concrete bridges are durable when they are designed and built properly. However, some of our bridges are deteriorating as a result of alkali-silica reaction, delayed ettringite formation, carbonation, sulfate attack, reinforcing bar corrosion, freeze-thaw damage, or other reasons.

As I frequently say to my students, identifying the problem correctly is more than 50% of its solution. The aforementioned problems are identifiable in routine bridge inspections. As a result, when they occur, bridge owners know about them. The question becomes how to consistently account for aging and deterioration effects in our structural evaluations. An experienced structural

engineer can make a series of conservative assumptions and analyze a structure to determine whether repair, rehabilitation, monitoring, or replacement is the most appropriate solution for a specific problem identified in the field. This is our current approach to finding solutions to problems revealed in field inspections. However, two major challenges stem from this approach.

### Establishing Standards for Identifying and Solving Problems

First, because the solutions generated by structural engineers reflect the engineer's individual experiences, the solutions chosen may vary greatly from engineer to engineer. As engineers, we are typically conservative in our approaches when we are uncomfortable about conditions that surround a field problem. Senior engineers can draw from their past experiences while deriving solutions; their familiarity with a challenging scenario gives them confidence so they do not simply default to the most conservative choice. In contrast, engineers who are less experienced may generate solutions that are more conservative, and perhaps more costly, for the same situation.

If our ultimate goal is the responsible allocation of resources available to us, and if lack of experience is the root cause of inappropriate or overly conservative solutions, it seems desirable to generate solutions for structural repair/retrofit that structural engineers and materials scientists of every experience level can use with confidence. Such solutions should be consistent with new design principles and concepts, and desired targets for reliability and conservativeness.

Remarkably, our colleagues at *fib* (International Federation for Structural Concrete) are working on

this issue. I am currently involved in the preparation of *fib's* next Model Code, which is intended to serve as a primary reference document for many national reinforced concrete design codes around the world. The next edition (i.e., Model Code 2020) will be used for both designing new structures and evaluating the existing inventory of structures (including structures experiencing concrete and reinforcement degradation) in a uniform, consistent, and rational manner with respect to structural safety and environmental impact. In other words, responsible allocation of resources is a priority for our colleagues worldwide who are contributing to Model Code 2020. Production of such reference documents is essential, and educators must include them in classes and curricula to prepare students who will tackle problems related to the nation's bridge inventory.

### Ensuring Knowledge Transfer

The second challenge we face as we monitor and maintain our bridge inventory is training the structural engineers who have already entered the workforce. Experienced engineers in the United States are retiring at a rapid pace, and that means institutional memory is being rapidly lost. Although knowledge transfer is taking place as senior engineers train and mentor junior colleagues before retiring, the sufficiency of this "organic" approach is open for debate.

In my view, in addition to this organic approach, we must develop means and methods to help surmount the growing experience and knowledge gap in the workplace. This is a big challenge, which must be addressed on two different levels. First, we must figure out how to create hands-on training opportunities where inspectors and bridge engineers of the future can be

trained in a consistent manner. Second, we must integrate technology into our thinking about how we share knowledge and promote standards. When I watch my two kids (ages 20 and 18) use their smartphones, tablets, and computers, I cannot help but think that the new reality does exist on the internet. Therefore, maintaining and digitizing what is known to us is extremely important. We should create a robust national repository (or repositories) where case studies, knowledge, and solutions can be easily shared with the next generation of bridge engineers. Integration of those resources with repair codes and guidelines will be essential. Soon, perhaps in the next decade or so, paper copies of codes and standards (including repair standards) will be superseded by entirely digital versions. We will need to ensure that accurate and endorsed

means and methods for repairing, retrofitting, and/or repurposing the existing inventory of bridges are discoverable and up-to-date online.

### Conclusion

Our nation's leaders are contemplating authorizing trillions of dollars to maintain and improve our transportation infrastructure. At this critical moment, the challenge of how to deal with the existing bridge inventory in a responsible and consistent manner, while being mindful of the resources available to us, is a challenge we must accept. We need to collaborate with and learn from colleagues tackling similar problems in countries with older transportation infrastructures. We also need to introduce new classes, or new modules in existing classes, to our curricula. And we need to expand the means and methods by which we provide training

to junior engineers in the workplace, share knowledge, and keep standards up to date. Collectively, such strategies may help us succeed in the most ambitious infrastructure endeavor since the massive expansion of our highway system after World War II. **A**

### EDITOR'S NOTE

*The eLearning courses developed through a joint partnership of FHWA, AASHTO, and PCI are a step in the right direction for providing basic training related to concrete bridges. Courses such as In-Service Analysis Load Rating (T710) provide guidance for evaluating our bridge inventory and are available at no charge. This course and others developed through this same partnership are available at <http://elearning.pci.org/>.*

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# InfoBridge: Easy Access to the National Bridge Inventory and Much More—Part 1



by Dr. Jean A. Nehme, Federal Highway Administration

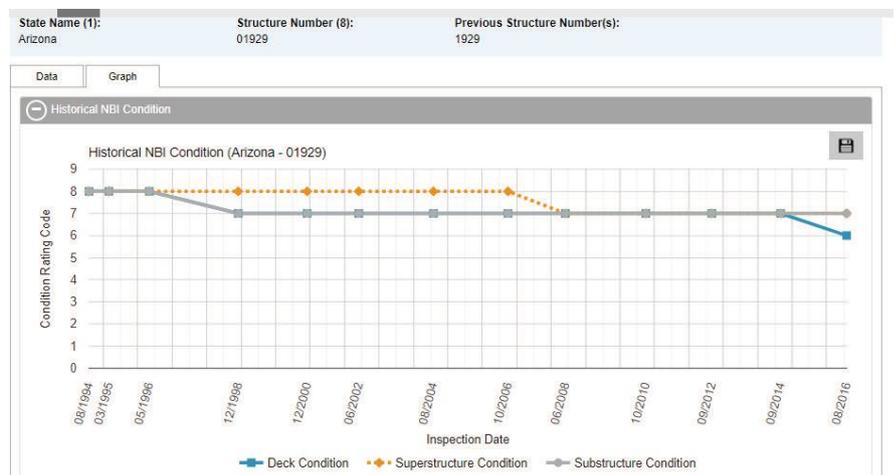
In January 2019, the Federal Highway Administration (FHWA) launched the Long-Term Bridge Performance (LTBP) InfoBridge web portal (<https://infobridge.fhwa.dot.gov>). This article, the first in a two-part series, offers a high-level overview of InfoBridge. Part 2 will delve into more advanced features.

## What Is InfoBridge?

InfoBridge is a centralized gateway for quick and efficient access to bridge performance-related data and information. It includes tools to facilitate bridge data analytics and provides for storage, retrieval, dissemination, analysis, and visualization of data collected through state, national, and LTBP program efforts. Thus, the portal helps users holistically assess bridge performance on a network or individual bridge basis.

The user-friendly portal has intuitive features for finding, viewing, and analyzing bridge performance information. Users can also efficiently share data selections and summary reports. By enhancing our understanding of the performance of highway bridge assets, InfoBridge supports more efficient design, construction, rehabilitation, maintenance, preservation, and management of those assets.

InfoBridge was developed to advance the goals of the LTBP program, which is a long-term FHWA research effort to collect high-quality bridge data from a representative sample of highway bridges nationwide. The LTBP program—which is authorized by Congress under the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users—helps the bridge community better understand bridge performance. Originally intended for researchers and state department of transportation bridge engineers, InfoBridge can benefit many others, including consulting engineers, local government asset managers, and transportation planners. Access to InfoBridge is free and does not require a username or password.



For a selected bridge, the Historical NBI Condition feature shows variance in condition rating codes for the bridge deck, superstructure, and substructure with respect to inspection date. All Figures: Federal Highway Administration.

## Available Data

Three major data categories are currently available through InfoBridge:

- National Bridge Inventory (NBI) data: Since 1983, bridge owners have submitted NBI data to FHWA annually. Starting in 2015, National Bridge Elements (NBE) data for bridges located on the National Highway System have been included in the data set.
- Climate data: Annual climate data dating back to 1983 are available. Currently, data on the number of snowfalls and freeze-thaw cycles are included. Additional attributes will be added in future releases of InfoBridge. The source for climate data is the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2).
- LTBP program data: This data set encompasses different types of data ranging from design and construction information on 1600 bridges to raw and processed non-destructive evaluation data for around 30

bridges, including contour plots displaying areas of deterioration.

In the future, FHWA will integrate other categories of data sets such as performance research results on weathering steel and timber bridges. Additional data will be obtained through cooperation with research efforts that collect bridge performance data.

## InfoBridge Components and Features

InfoBridge includes multiple components and features that facilitate data viewing, visualization, and analytics. The basic features are described here.

### Find Bridges

The *Find Bridges* feature consists of data filters within the categories of NBI, NBE, and LTBP data. Users can query the database and view the results in both a tabular format and on a map. Users can also see performance data and statistics on the dashboard or save query and filter criteria for future use.

## Advanced Find

While the *Find Bridges* feature works for basic data attributes, the *Advanced Find* feature enables users to narrow their selection criteria by using all data attributes available under different categories. This feature works in conjunction with the *Find Bridges* feature, allowing users to perform sophisticated data searches on the available bridge data.

## Map Find

The *Map Find* feature displays the selected bridges on an interactive map. Users can change the selection criteria using drawing tools and view the results on the map. This feature can be used independently or in conjunction with the *Find Bridges* and *Advanced Find* features to further refine the selected data set.

## Performance Dashboard

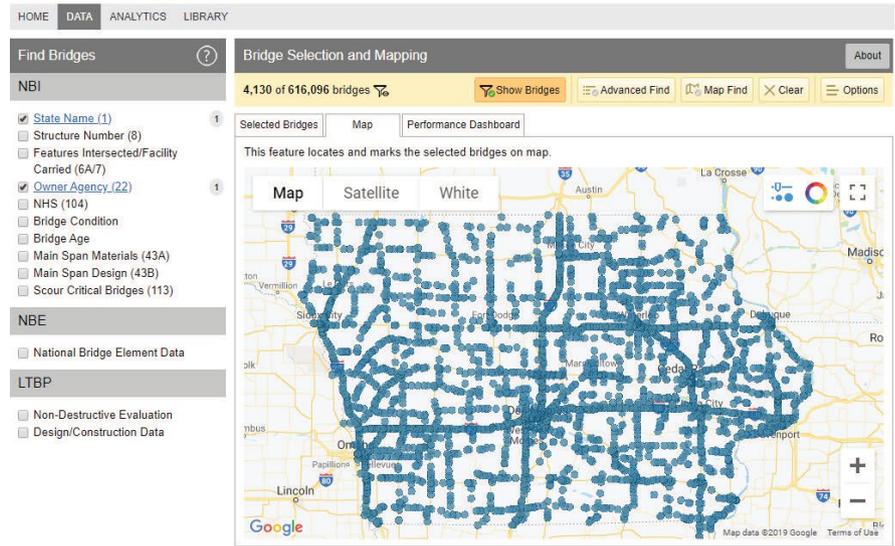
The *Performance Dashboard* displays bar charts, tabulated summaries, and historical performance graphs corresponding to the set of selected bridges. It enables users to view performance summaries at a glance. As in all InfoBridge modules, the user can print or download the data displayed on the dashboard.

## Bridge Information

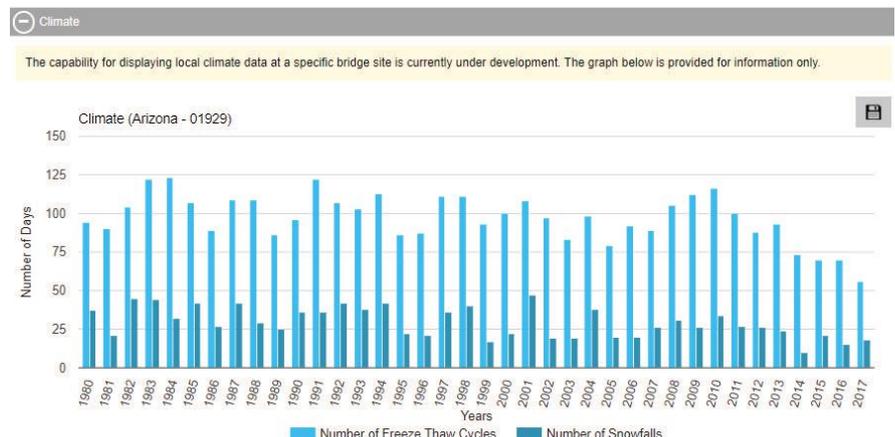
Selecting a bridge from the *Selected Bridges* table or *Map* tab displays the bridge details under the *Bridge Information* section. This section is organized into categories with *Overview*, *NBI*, *NBE*, *Climate*, and *LTBP* tabs. The *Overview* tab displays the key data attributes and overall extent of the data available for the selected bridge. The remaining tabs provide access to the bridge data for the corresponding data category. A *Bridge Summary Report* can be generated from the *NBI* tab for the selected bridge and a chosen submittal year.

## Next Steps

In 2020, the LTBP program will incorporate bridge deterioration models into InfoBridge. One model will use historical NBI data to forecast future conditions of concrete bridge decks. The program is also conducting research on using a combination of statistical analysis techniques, namely, survival analysis and Markov chain theory, to accomplish this task. 



One of the InfoBridge search options enables users to locate and map bridges and conditions within selected criteria. For example, this map shows the results of a search for all bridges in the Iowa state highway system.



The Climate feature ultimately will show the number of annual freeze-thaw cycles and snowfalls at the selected bridge location.

## For More Information on InfoBridge

Visit <https://infobridge.fhwa.dot.gov> and <https://highways.dot.gov/long-term-infrastructure-performance/ltbp/long-term-bridge-performance>, or contact Jean Nehme at 202-493-3042 or [jean.nehme@dot.gov](mailto:jean.nehme@dot.gov).



# Delaware

by Jason Hastings, Delaware Department of Transportation

Like every other state, Delaware faces challenges inherent to its terrain and environment. The biggest challenges for the Delaware Department of Transportation (DelDOT) involve coastal and tidal conditions—Delaware is the closest state to sea level (lowest mean elevation). Also, many small towns along the Delaware coast have single-access roadways, which means bridges must be replaced quickly to minimize the effects of closed roads and construction on communities. These issues have led DelDOT to seek new cost-effective and efficient techniques and components for bridge projects.

## Design and Material Choices

Annually, about 20 Delaware bridges are rehabilitated or replaced. District maintenance

labor forces or their open-end contractors perform minor repairs, preventive maintenance, or emergency repairs on another 35 to 40 bridges per year.

DelDOT designs about half of the state's bridges. When projects are complex, complicated by coordination of environmental or railway concerns, or DelDOT staff has limited availability, consultants may be hired.

In about two-thirds of all designs, concrete bridges meet the state's needs. Concrete structures are the default choice in all marine conditions because they are so durable. Epoxy-coated reinforcing bars are used exclusively for conventional reinforcement, and a low-permeability concrete mixture has become standard for these situations. Prestressed concrete piles are used in coastal areas, with

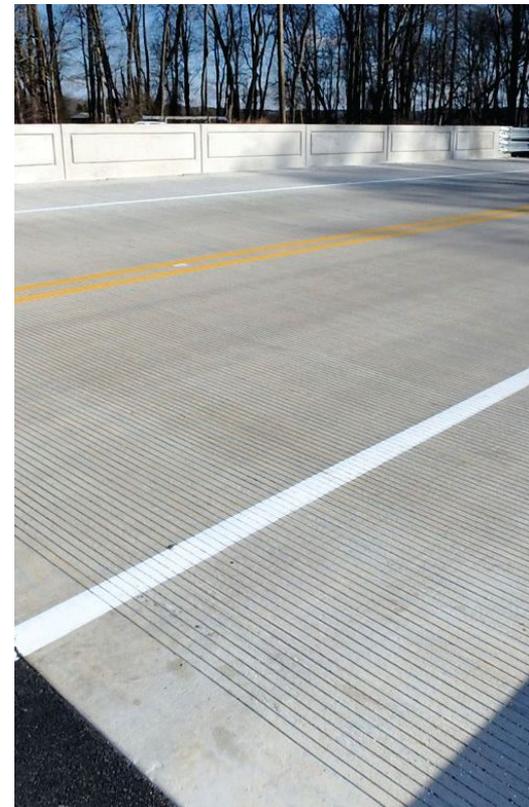
little use of steel H-piles and monotubes, especially with pile bents.

DelDOT has a long history of using concrete adjacent box beams and voided slabs because they provide an efficient and cost-effective approach. Northeast Extreme Tee (NEXT) beams are also being used on more projects. They have no hidden areas where water can collect, which can be an issue with voids in other shapes. Their superstructure depth is similar to that of box beams, so NEXT beams can easily replace existing beams on most short- to medium-span (about 40 to 90 ft) bridges over waterways.

The Christina River Bridge in Wilmington, Del., is a recent example of an outside-of-the-box concrete solution; it is the first spliced precast concrete girder design in the state.



Workers place ultra-high-performance concrete (UHPC) in shear joints for Bridge 3-558 on Daisy Road over Pocomoke River in Millsboro, Del. This was the first use in the state of UHPC joints in a prestressed concrete adjacent box-beam bridge with a cast-in-place deck. All Photos and Figures: Delaware Department of Transportation.



Completed deck on Bridge 3-558 on Daisy Road. The structure has experienced no deck cracking since its completion in early 2016.



*The Prime Hook Road Bridge near Milford, Del., is located in a low-lying tidal area with frequent flooding. Northeast Extreme Tee beams with ultra-high-performance concrete (UHPC) joints and a thin epoxy overlay were used to provide high durability.*

The \$26.7 million, 470-ft-long multimodal bridge features two 11-ft-wide travel lanes plus a 14-ft-wide shared-use path. (See the Project article in this issue of *ASPIRE*®.)

## Success with Ultra-High-Performance Concrete Joints

To increase the serviceability and durability of bridges, DelDOT experimented with using ultra-high-performance concrete (UHPC) instead of conventional grout for shear joints. The goal was to determine how best to eliminate joint cracking, which could allow chloride penetration into the superstructure.

The concept was tested on Bridge 3-558 on Daisy Road over Pocomoke River in Millsboro, Del., a rural area in the southern part of the state. The bridge, which was opened to traffic in early 2016, features prestressed concrete adjacent box beams with UHPC shear keys and a cast-in-place deck. It was constructed in three weeks (one week under the deadline). A 100-year service life is anticipated, although studies of UHPC materials suggest that the bridge could be in service even longer. To date, there has been no cracking in the deck.

Encouraged by this result, DelDOT used UHPC for the joints on another project, the Prime Hook Road Bridge near Milford, Del. Situated in a low-lying area with tidal conditions and frequent flooding, the new bridge was designed to accommodate canals built by the Army Corps of Engineers to help rebuild the Prime Hook National Wildlife Refuge tidal marsh. The bridge, completed in February 2017, features NEXT beams with UHPC joints and a thin epoxy overlay. To date, the UHPC joints have completely resolved issues with cracking. On a

rehabilitation project now out for bids, UHPC shear joints are offered as an option.

The results so far have been so satisfying that DelDOT made the use of UHPC for shear joints a standard in the state bridge design manual, replacing the previous details that included welded plate or angle shear connectors, grouted shear keys, and post-tensioned tie rods. The test projects have shown that superstructure replacements can be completed in approximately 30 days using the UHPC joints compared with 75 to 90 days of construction time using the previously required details.

## Concrete Deck Alternatives and ABC Techniques

The positive experience with UHPC joints has encouraged DelDOT to explore alternative overlay solutions, such as polyester polymer concrete overlays. DelDOT has also contemplated returning to hot-mix asphalt overlays with a membrane, considering the protection the UHPC joints provide.

When Delaware bridges are inspected for rehabilitation consideration, the substructures are often in good shape, with only the deck needing rehabilitation. Overlays can extend the service life of the deck significantly. In some cases, bridge service life can be doubled just by replacing or rehabilitating the deck. That says a lot about the quality and durability of the concrete components used originally.

Precast concrete elements aid with accelerated bridge construction (ABC), which is often used in Delaware for bridges on single-access roadways into small coastal towns. Because components are cast in a plant and then quickly assembled at the site, traffic interruptions are limited. Also, because precast concrete is highly



*Detail of a 9-in.-wide deck joint with epoxy-coated headed reinforcement, which will be filled with UHPC, on the Prime Hook Road Bridge.*

durable, bridges can be located closer to water than other designs would allow.

DelDOT used precast concrete deck panels with UHPC joints as an ABC technique for the first time on Bridge 1-717 on Interstate 95 (I-95) northbound over State Route 1 in Christiana, Del. The bridge is the state's busiest interchange, with average daily traffic of nearly 200,000 on the two roads; therefore, project efficiency was essential. The project was completed in November 2016, after the entire deck was replaced in two phases totaling 32 working days.

## Precast concrete elements aid with accelerated bridge construction, which often is used in Delaware for bridges on single-access roadways into small coastal towns.

ABC techniques are also used for bridge replacements. Built in 2017, Bridge 1-438 on Blackbird Station Road over Blackbird Creek in Townsend, Del., is the state's first all-precast concrete bridge (with precast/prestressed concrete piles, abutments and wingwalls, and adjacent box beams). On this project, the state also used a UHPC overlay for the first time. A Federal Highway Administration grant to study this use of UHPC funded the overlay, which is performing well to date and exhibiting no cracking.

Completed in November 2016, Bridge 1-717 on Interstate 95 northbound over State Route 1 in Christiana, Del., was the first bridge in the state to use precast concrete deck panels with ultra-high-performance concrete joints. The bridge is Delaware's busiest interchange, averaging nearly 200,000 vehicles per day on the two roads. The work was completed in 32 days.



## Improved Monitoring and Inspection

DelDOT's Bridge Management Group has begun using impact-echo inspection technology for concrete bridge decks on all major roads. The method uses sonar techniques to evaluate deck delamination, thereby identifying decks that need attention before they otherwise would be considered for repair/replacement, and before deterioration can be visually observed. So far, this technology has been used on all interstates and four other major traffic corridors in Delaware.

## DelDOT's Bridge Management Group has begun using impact-echo inspection technology for concrete bridge decks on all major roads.

In efforts to improve preventive maintenance of concrete decks, DelDOT also has implemented a deck-sealing program to delay deterioration and extend the life of the concrete bridge deck inventory. Each deck is resealed every four years, with existing cracks along the entire deck being sealed with a methyl methacrylate compound and a silane penetrating sealer. In the database, decks are identified with the date of the last sealer application to trigger the next resealing.

DelDOT has taken its monitoring focus further by producing its first "smart" bridge, the Indian River Inlet Bridge in Bethany Beach, Del. The bridge is the first smart cable-stayed bridge

in the United States. Completed in 2012, the bridge features post-tensioned, continuous edge girders with pretensioned concrete cross beams. (For more on this project, see the Winter 2012 issue of *ASPIRE*.)

The bridge has built-in sensors that continually monitor the structure for loading, temperature, wind speed, and other variables. DelDOT is working with the University of Delaware to gather and evaluate the data in the hope that this information can improve long-term management of the bridge. Load testing is performed every two years to evaluate changes in loading or behavior of the primary load-carrying components. The sensors will also alert DelDOT if preset thresholds are triggered, indicating a potential concern for the cable stays or the edge girders—so far, this has not occurred.

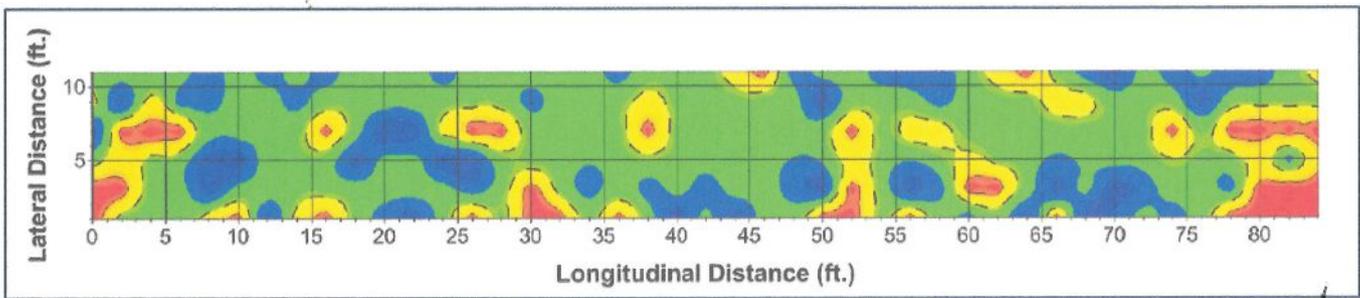
## Construction Manager/General Contractor Projects

The Delaware state legislature recently approved the use of construction manager/general contractor (CM/GC) contracting methods for up to 10 projects. The CM/GC model is seen as a way to improve efficiency, especially on ABC projects and high-profile, complex bridges, particularly those that deal with high volumes of traffic and utility or railway issues.

CM/GC is being used on a rehabilitation project currently underway in Rehoboth Beach, Del., a resort area. DelDOT intends to collaborate with the contractor to create a plan to perform the work in only one off-season. Using a design-bid-build approach would have taken two off-seasons, extending the project and increasing



Adjacent box beams with special shear key detail for UHPC shear connections on Bridge 1-438 on Blackbird Station Road over Blackbird Creek in Townsend, Del. (left). This was Delaware's first all-precast-concrete bridge, featuring precast/prestressed concrete piles, abutments, and adjacent box beams. A UHPC overlay, which was used on the bridge as a pilot study funded by the Federal Highway Administration, is being placed in the right photo.



A sample impact-echo analysis showing data received when a concrete bridge deck is tested. The system has been used on all interstates and four major traffic corridors in Delaware to evaluate deck delamination and identify decks that need rehabilitation earlier than anticipated.



The Delaware Department of Transportation's first "smart" bridge, the Indian River Inlet Bridge in Bethany Beach, was completed in 2012. It features post-tensioned, continuous concrete edge girders with pretensioned concrete cross beams. The bridge has sensors that continually monitor the structure for loading, temperature, wind speed, and other variables.

user costs substantially.

DelDOT is also using CM/GC for the \$200 million I-95 rehabilitation project to begin in 2021. Traffic will divert onto one side of I-95, then the other, to keep the roadway and all bridges open while work progresses over two years. Rather than stagger construction over four or five years, DelDOT decided to combine it into a single two-year effort, using the CM/GC approach to deliver the project more efficiently.

DelDOT plans to use the CM/GC delivery method when it is the most efficient approach. Additionally, DelDOT will continue to investigate new technologies and techniques and look for innovative ways to deliver upgraded bridges that help drive down user costs. 

Jason Hastings is chief of bridges and structures in the Delaware Department of Transportation's Bridge Section in Dover.

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# Mitigating Deicing Salt Damage to Concrete Pavements and Bridges

by Dr. Prannoy Suraneni, University of Miami, and Dr. Jason Weiss, Oregon State University

**D**eicing salts, which are typically rock salt and other chloride-based salts such as calcium chloride ( $\text{CaCl}_2$ ) and magnesium chloride ( $\text{MgCl}_2$ ), are commonly used in the United States to melt ice on the surface of pavements and bridges.<sup>1,2</sup> These chloride-based salts are an economical technology that increases driver and pedestrian safety, but they may have negative effects on concrete pavements and bridges, such as salt scaling and steel corrosion. These salts also exacerbate freeze-thaw damage in concrete.

While the damaging effects of salts are understood reasonably well, an additional form of chemical damage associated primarily with the use of high concentrations of  $\text{CaCl}_2$  and  $\text{MgCl}_2$  has been recently discovered. Because the use of such salts has been increasing, concrete pavements and bridge decks are increasingly showing signs of this type of chemical damage, which occurs due to the formation of a deleterious phase known as calcium oxychloride (CAOXY) and forms primarily along the joints and at low points in concrete pavements and bridge decks (Fig. 1).<sup>1,2</sup>

This type of damage is generally visible around the end of the first decade of service life and can be expensive to repair. Notably, CAOXY damage does not require freezing temperatures to occur and can happen at any time of the year. This article summarizes CAOXY damage mechanisms, testing methods, and damage mitigation. We hope that sharing this information will encourage others to adopt steps to minimize such damage and extend the life of our concrete infrastructure. Further details about CAOXY damage are found in references 1–3.

### Damage Mechanisms

When chloride-based salt solutions are applied on concrete surfaces, they are

slowly transported inside the concrete. A portion of these chlorides from  $\text{CaCl}_2$  then reacts with calcium hydroxide ( $\text{Ca(OH)}_2$ ), which is a phase that is found in most concretes, leading to the formation of the deleterious CAOXY phase, as shown in the following equation:<sup>1–4</sup>



The CAOXY causes damage and loss of strength and elastic modulus because it is expansive, cracking the surrounding matrix.<sup>1</sup>

### Testing Methods

Historically, damage caused by CAOXY formation was assessed by submerging concrete in concentrated  $\text{CaCl}_2$  or  $\text{MgCl}_2$  solutions and studying the reduction of properties such as compressive strength or elastic modulus over time.<sup>5</sup> Such testing provides valuable information; however, it is time-consuming. Nondestructive methods such as ultrasonic pulse velocity and bulk resistivity can monitor concrete property evolution and reduce testing effort.

Thermogravimetric analysis can be used to estimate the amounts of CAOXY that can potentially form in cement

pastes. In this test, a small amount of powdered cement paste is heated to over  $600^\circ\text{C}$ ; the mass loss between  $380^\circ\text{C}$  and  $460^\circ\text{C}$  is used to quantify the amount of  $\text{Ca(OH)}_2$ . The relationship between  $\text{Ca(OH)}_2$  and CAOXY amounts that form in cement pastes is linear; therefore, the  $\text{Ca(OH)}_2$  amount can be used to estimate the CAOXY amount.<sup>1,3</sup> A limitation of this analysis is that the  $\text{Ca(OH)}_2$  must be accessible to the salt for it to react, which may not always happen when the concrete has carbonated.<sup>6</sup>

Low-temperature differential scanning calorimetry (LT-DSC) is a direct method to determine CAOXY amounts. Powdered cement paste is mixed with an equal mass of 20%  $\text{CaCl}_2$  solution. The mixture is then inserted into the LT-DSC device and subjected to a cooling-heating cycle ranging in temperature from  $-90^\circ\text{C}$  to  $50^\circ\text{C}$ . The heat associated with the formation of CAOXY can be measured, and the amount of CAOXY can then be computed. This method has been adopted by the American Association of State Highway and Transportation Officials as AASHTO T365.<sup>7</sup>

### Damage Mitigation

Because the primary phase that leads to concrete damage is  $\text{Ca(OH)}_2$ , damage can be reduced by reducing

Figure 1. Example of concrete pavement joint damage showing cracking parallel to the joint and spalling and cracking at the joint. Photos: Jason Weiss.



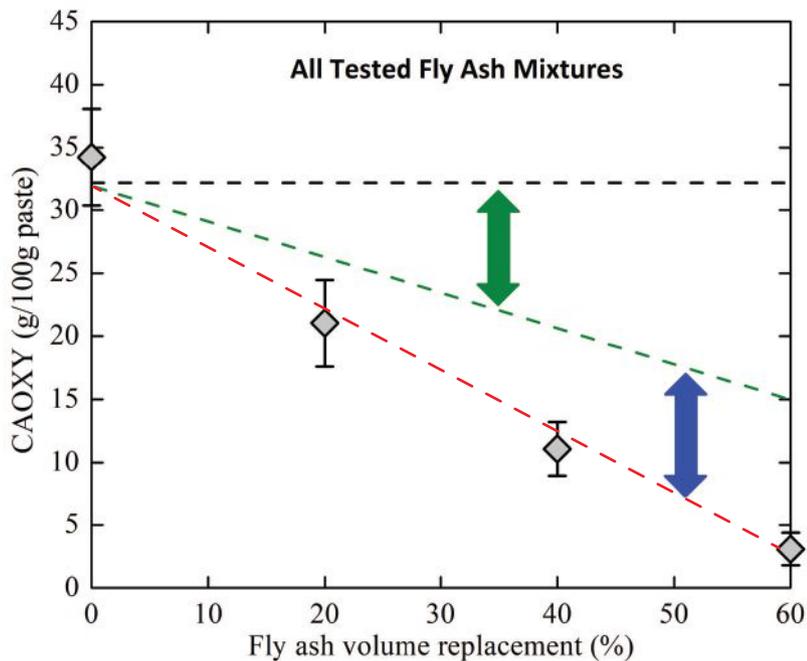


Figure 2. The reduction in CAOXY content as fly ash content increases in cementitious pastes. This reduction results from a combination of dilution (green arrow = less cement in the paste) and pozzolanic reaction (blue arrow = fly ash reacts with calcium hydroxide to form non-CAOXY phases). Figure: Adapted with permission from Reference 8.

Ca(OH)<sub>2</sub> content in concrete. The use of concrete containing supplementary cementitious materials such as fly ash and slag is an easy and practical way to reduce the formation of CAOXY and therefore the damage caused by it (Fig. 2).<sup>1,8</sup> These materials reduce the Ca(OH)<sub>2</sub> content by dilution (reducing the amount of cement) and pozzolanic reaction (materials react with Ca(OH)<sub>2</sub> to form other phases). The exact amounts of fly ash and slag required to mitigate damage depend on several factors; in most cases, the use of these materials as more than 30%–35% of the cementitious materials is likely to minimize damage.<sup>1,8</sup> The amount of CAOXY found through LT-DSC decreases linearly as the amount of fly ash or slag increases.

Adequate air entrainment is another effective way to reduce damage. The role of air in damage mitigation is complex, but one effect of air is that it acts as a valve to reduce pressure by providing space for the expansive CAOXY phase to form. Concrete mixture proportions with air contents of 6% or greater show reduced CAOXY damage.<sup>1,5</sup> However, as air voids fill over time due to the deposition of expansive phases, their usefulness in damage mitigation is reduced.

Other ways to reduce damage include the following:<sup>1</sup>

- Use blends of deicing salts to reduce the amount of reactive salt.
- Use concrete carbonation because the carbonation reaction consumes Ca(OH)<sub>2</sub>.
- Use concrete topical treatments to reduce the ingress of salts.

### Summary

This article describes a source of cracking and spalling damage in concrete pavements and bridges associated with the use of calcium chloride and magnesium chloride salts. The recently developed LT-DSC test method adopted as AASHTO T365 can be used to evaluate the susceptibility of concrete to this kind of damage. Practices to mitigate damage caused by CAOXY include the use of air entrainment, supplementary cementitious materials, and topical treatments. ▲

Dr. Prannoy Suraneni is an assistant professor in the civil, architectural, and environmental engineering department at the University of Miami in Coral Gables, Fla., and Dr. Jason Weiss is a professor and head of the School of Civil and Construction Engineering at Oregon State University in Corvallis.

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# The Effects of Strand Debonding

by Dr. Oguzhan Bayrak, University of Texas at Austin

To control stresses in the end regions of pretensioned concrete girders, strands are either harped or debonded. Some state departments of transportation (DOTs) have policies to discourage debonding because they prefer to harp strands in the end regions. Other DOTs prefer debonding over harping strands, citing concerns related to potential safety hazards associated with deflecting highly tensioned strands, as well as overall practicality. In fact, both methods have been successfully used since pretensioned concrete beams have gained widespread use in the United States. New debonding rules may change the way designers approach controlling stresses in end regions, and the design implications of the forthcoming changes are explored in this article.

As I mentioned in the LRFD article in the Fall 2019 issue of *ASPIRE*<sup>®</sup>, American Association of State Highway and Transportation Officials (AASHTO) Committee T-10 members have worked hard to improve the debonding rules based on the knowledge accumulated over decades of experience. The 25% maximum debonding limit in the *AASHTO LRFD Bridge Design Specifications*, 8th edition,<sup>1</sup> will give way to a series of rules in the 9th edition (scheduled to be published in 2020) stipulating that a maximum of 45% of the strands can be debonded in any single row. In this way, the theoretical upper bound on debonding can be perceived to be 45%. Additional rules limit debonding of strands underneath the webs, require that symmetry is maintained about the vertical axis that passes through the center of gravity of the cross section, and require alternating bonded and debonded strands in a row or in a column in the strand group. In addition, all strands within the horizontal limits of the web when the bottom flange-to-web width ratio  $b_f/b_w$  is greater than 4 are to be bonded. When all the rules explained in my previous article are applied to common pretensioned concrete girder sections, the actual upper limit on debonding ends up being less than 45%. Meeting all the new rules of debonding implies that roughly one-third of the

strands can be debonded in the end regions of pretensioned concrete girders.

One important note is that debonding in the end regions must be implemented carefully. Strands (i.e., the longitudinal ties for flexural resistance) need to have adequate capacity and be properly anchored at the supports of girders (**Fig. 1**).<sup>1</sup>

Article 5.7.3.5 of the AASHTO LRFD specifications provides equations that shall be met to ensure an adequate tie force is provided considering available strand anchorage. The associated equations are as follows.

At each section, strength of the longitudinal tie (left side of the inequality in Eq. [5.7.3.5-1]) shall be greater than the demand on the tie (right side of Eq. [5.7.3.5-1]).

$$A_{ps}f_{ps} + A_s f_y \geq \frac{|M_u|}{d_v \phi_f} + 0.5 \frac{N_u}{\phi_c} \left( \left| \frac{V_u}{\phi_v} - V_p \right| - 0.5V_s \right) \cot \theta \tag{5.7.3.5-1}$$

At the inside edge of a bearing, Eq. 5.7.3.5-1 can be simplified as:

$$A_s f_y + A_{ps} f_{ps} \geq \left( \frac{V_u}{\phi_v} - 0.5V_s - V_p \right) \cot \theta \tag{5.7.3.5-2}$$

Setting moment and axial load equal to zero in Eq. (5.7.3.5-1) produces Eq. (5.7.3.5-2). Note that  $V_s$  appears on the right side of Eq. (5.7.3.5-1) as a negative quantity, which indicates that adding stirrups effectively reduces the demand on the longitudinal tie. However, the  $V$  used in the equation cannot be greater than  $V_u/\phi_v$ . That is, adding stirrups can only reduce the demand on the longitudinal tie up to a point. When the upper limit on  $V_s$  is inserted in Eq. (5.7.3.5-2), the minimum value for the longitudinal tie force can be computed using the following equation:

$$A_{ps} f_{ps} + A_s f_y \geq \left( 0.5 \frac{V_u}{\phi_v} - V_p \right) \cot \theta$$

The effect of adding stirrups on the demand for the longitudinal tension tie is presented graphically in **Fig. 2**. The typical inclination of the compression field in a pretensioned girder is 25 to 30 degrees, as depicted in Fig. 2a, for an assumed truss geometry. In this case, the full tie force  $T$  has to be properly anchored at the support, which may be difficult. By providing the maximum allowed shear reinforcement, a two-panel truss mechanism is formed to transfer the load into the support, and the demand on the longitudinal tie force to be anchored at the support is reduced by approximately 50%. As previously discussed, using the quantity of stirrups corresponding to the maximum limit on  $V_s$  forces the inclination of the compression field to be 45 degrees, rendering the relevant provisions of the AASHTO LRFD

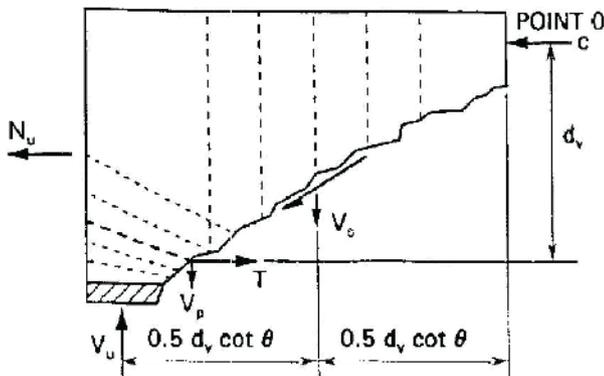
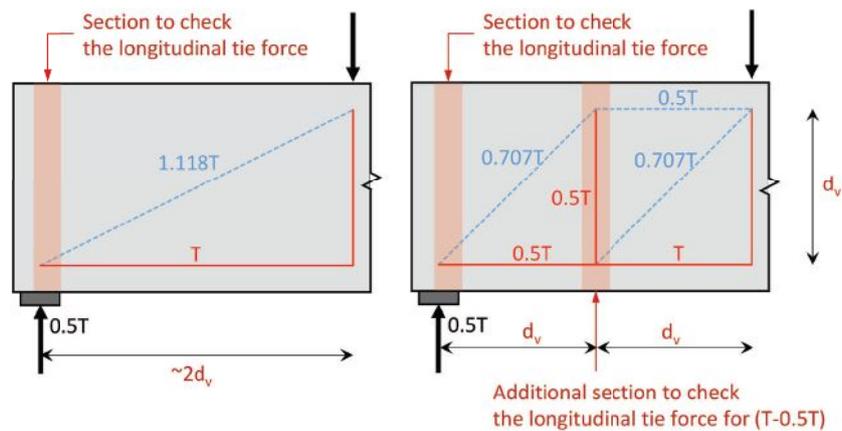


Figure 1. Anchorage of a longitudinal tie. AASHTO LRFD specifications C5.7.3.5-1.<sup>1</sup>



a. Tie Force to be Anchored at the Support =  $T$

b. Tie Force to be Anchored at the Support =  $0.5T$

Figure 2. Influence of maximum allowed shear reinforcement on longitudinal tie anchorage demand. Figure: Oguzhan Bayrak

specifications equivalent to the *fib* (International Federation for Structural Concrete) Model Code 2010 for reinforced concrete design.<sup>2</sup>

The requirement to check the force in the longitudinal tie has been in effect since the 1st edition of the AASHTO LRFD specifications (1994). The 25% limit placed on strand debonding in the current specifications made this longitudinal tie check a seldom-necessary backstop, even though it was a requirement of the specifications. As we move forward, the implementation of new debonding rules will, in some cases, result in a significantly larger percentage of the strands being debonded at the ends of simply supported pretensioned concrete girders. In these cases, we must be especially careful about meeting this requirement of the specifications.

Finally, if we take a high-level look at strand debonding, we must acknowledge that higher percentages of debonded strands reduce the level of precompression at the ends of pretensioned concrete girders. This reduction in precompression results in

a reduction in concrete contribution to shear strength. For these reasons, debonding must be done judiciously. Overall, concrete bridges and pretensioned concrete elements offer excellent durability while maintaining cost-effectiveness for a great number of bridges across the United States and worldwide. By recognizing the structural benefits (e.g., reduced end-region cracking) and costs (e.g., reduced level of precompression in the end regions) when using debonded strands, we can maintain or improve the durability of our concrete bridges.

## References

1. American Association of State Highway and Transportation Officials (AASHTO). 2017. *AASHTO LRFD Bridge Design Specifications*, 8th ed. Washington, DC: AASHTO.
2. *fib* (Federation Internationale du Beton/International Federation for Structural Concrete). 2013. *fib Model Code 2010 for Concrete Structures*. Lausanne, Switzerland: *fib*.



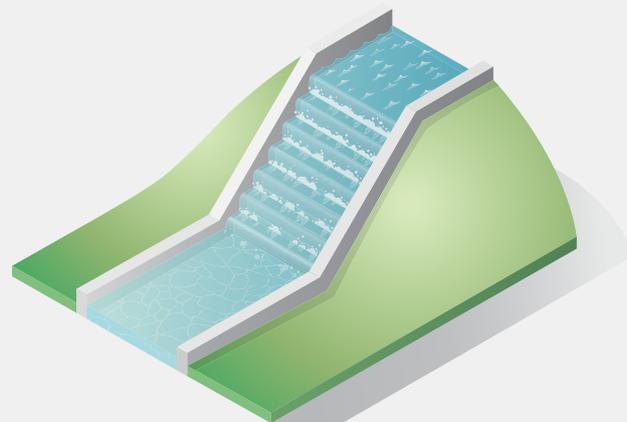
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# Engineering's Professional Obligation

by Leon H. Grant, Coreslab Structures (Conn.) Inc.

In their professional lives, engineers must be accountable for how they perform their key responsibilities every day, on every project they undertake. For students in engineering schools throughout Canada, this duty is brought home to them by the Ritual of the Calling of an Engineer, also known as the Iron Ring Ceremony, which is held during their senior year.

This ritual, which uses a text by Rudyard Kipling, began in 1922 and remains in place today. It was conceived by seven past-presidents of the Engineering Institute of Canada, led by Professor H.E.T. Haultain of the University of Toronto, who asked Kipling to write the wording.<sup>1</sup> Their plan was to

create a standard of ethics that could be reinforced through a ceremony, culminating with the presentation of a metal ring to each graduate to emphasize the standard's importance. The seven officials presided over the ceremony as the Corporation of the Seven Wardens.

## The Ritual Explained

In his notes, Kipling explained the purpose of the ceremony. "The Ritual of the Calling of an Engineer has been instituted with the simple end of directing the young engineer toward a consciousness of his profession and its social significance and indicating to the more experienced engineer their responsibilities in welcoming and

supporting the newer engineers when they are ready to enter the profession."<sup>1</sup>

Each year, one of the Corporation's 27 "camps" will oversee the ritual for each of the 43 universities granting engineering degrees in Canada; rituals are held at different times and can be performed in a variety of ways. Universities may give notice of the invitation-only ceremony, but participation in the ritual may not be used for advertising purposes.

At the ceremony, the students repeat an oath, known as the Obligation, which expresses their intention to uphold the engineer's duties and responsibilities. Following the oath, an "iron" ring (made of iron or stainless steel) is placed on the little finger of the engineer's working hand. The ceremony certificate explains that the ring shall serve "as a reminder to yourself and to others that you have taken this Obligation." The ring is to be worn on the engineer's working hand because it is intended to come into contact with drawings or documents being prepared.

**At the ceremony, the students repeat an oath, known as the Obligation, which expresses their intention to uphold the engineer's duties and responsibilities.**

The program was created following a tragic bridge accident in Quebec in 1907 (see the sidebar for more information). Errors made in the design and construction of that bridge harmed the engineering profession's reputation, and the seven wardens hoped that the oath and ceremony would demonstrate

## Quebec Bridge Disaster Inspires Ceremony

The Iron Ring Ceremony came about as a response to the Quebec Bridge disaster on August 29, 1907, in which a steel bridge under construction over the St. Lawrence River collapsed, killing 75 of the 86 workers constructing the cantilevered segment. Some were crushed, some were killed by the fall, and others drowned.

The bridge, designed by Theodore Cooper, was intended to be an engineering marvel—the largest structure of its kind and the longest bridge in the world. To help economize, Cooper extended the bridge's spans. Government engineers thought the design was unsafe, but Cooper's plan won out.

When deflection issues began to arise, their significance wasn't understood. Then, when Cooper finally wired the contractors at the site to halt work until the deflection issues were considered, his instructions were ignored. Ultimately, two bottom chords buckled, plunging the structure into the water below.

After the disaster, engineers would visit the site to be reminded of the results of human

error and the importance of not stretching designs beyond physical capabilities. Cooper took much of the blame, while the bridge company was criticized for putting profits over safety.

Fifteen years later, the seven past-presidents of the Engineering Institute of Canada, formed the idea of the Iron Ring Ceremony.

Leon Grant's Iron Ring adorns the little finger of his working hand, 46 years after he participated in the Ritual of the Calling of an Engineer. All Photos: Leon H. Grant.



the high standards that all engineers strive to achieve.

## The Lasting Impact of the Obligation

I took part in the Iron Ring Ceremony prior to my graduation from the University of New Brunswick in 1973, and its significance sticks with me to this day. The university's five-year engineering program was taught by full professors who had served in World War II or received their PhDs following the war. They had executed astonishing designs under the worst stress imaginable, and it was deeply moving to realize that they saw this ritual—a reminder of the need for professionalism—as an integral part of their instruction.

Before the ceremony occurred, our professors had already impressed upon us the responsibility and privileges of the

title of Professional Engineer. They were educators, mentors, and consultants to industry, legal, and engineering firms. During our fifth-year engineering law and ethics program, we were exposed to a variety of successes and failures in the engineering profession. The failures included the Quebec Bridge disaster that was the catalyst for the ceremony.

In March of our senior year, we were invited to the Iron Ring Ceremony. It included a first-class dinner, presentations by senior practicing engineers, and a ceremony attended only by those who had taken the Obligation or were graduating engineers. This ceremony represented the first official meeting of the entire class since we had separated into specific disciplines after our first year.

Afterward, we felt that we had taken the first step of our engineering career.

Even though most of us had job offers and would be receiving a diploma in May, the ceremony was the event that made it clear we were now entering a profession with privileges and responsibilities like no other.

The ceremony also reinforced to us that we must practice only within our competence, learn from the engineers who preceded us, and mentor those following us for life. It also was stressed that we must respect our peers without prejudice.

The certificate from the Iron Ring Ceremony is framed and has remained on my office wall since 1973. It includes the text of the Obligation we recited and serves as a reminder of our responsibility to uphold high standards of professionalism. I have no doubt that it is also prominent in many other engineers' offices across the country.

The standards represented by the Iron Ring and the Obligation drive engineers to strive to be the best, review every detail, and work closely with others on the construction team to ensure their designs meet the high standards expected of every engineer.

## Reference

1. The Calling of an Engineer. n.d. <http://www.ironring.ca>. Accessed November 15, 2019. 

## The Engineer's Obligation

The Obligation that engineers pledge during the Iron Ring Ceremony is printed on the certificate each engineer receives after its conclusion. It reads:

I, (engineer's name), in the presence of these my betters and my equals in the Calling, bind myself upon my Honour and Cold Iron, that, to the best of my knowledge and power, I will not henceforward suffer or pass, or be privy to the passing of, Bad Workmanship or Faulty Material in aught that concerns my works before men as an Engineer, or in my dealings with my own Soul before my Maker.

My Time I will not refuse; My Thought I will not grudge; My Care I will not deny towards the honour, use, stability and perfection of any works to which I may be called to set my hand.

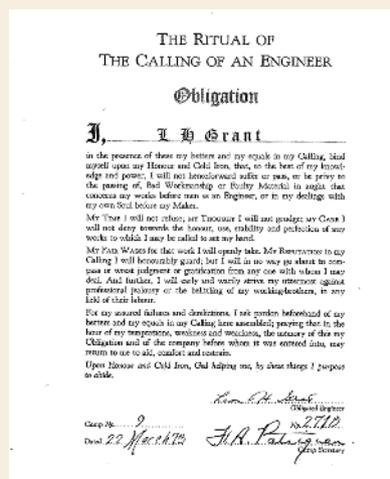
My Fair Wages for that work I will openly take. My Reputation in my Calling I will honourably guard; but I will in no way go about to compass or wrest judgment or gratification from any one with whom I may deal. And further, I will early and warily strive my uttermost against professional jealousy

Each engineer who undertakes the Ritual of the Calling of an Engineer receives a certificate that includes the Obligation and is signed by the "obligated engineer" and the camp secretary overseeing that university's program.

or the belittling of my working-brothers, in any field of their labour.

For my assured failures and derelictions, I ask pardon beforehand of my betters and my equals in my Calling here assembled; praying that in the hour of my temptations, weakness and weariness, the memory of this my Obligation and of the company before whom it was entered into, may return to me to aid, comfort and restrain.

*Upon Honour and Cold Iron, God helping me, by these things I purpose to abide.*



## EDITOR'S NOTE

*A Perspective article in the Fall 2017 issue of ASPIRE® described a similar ring ceremony performed in the United States as part of a broader discussion of the need to instill a sense of ethics in young engineers. In addition to describing the Canadian ceremony (for more information, see reference 1), this current article shares the lasting impression and significance of the ceremony for an individual engineer. It is important that those of us who are engineers be frequently reminded and continually aware of our solemn responsibilities as engineers.*

# CONCRETE CONNECTIONS

*Concrete Connections* is an annotated list of websites where information is available about concrete bridges. Links and other information are provided at [www.aspirebridge.org](http://www.aspirebridge.org).

## IN THIS ISSUE

### <https://www.nts.gov/investigations/AccidentReports/Reports/HAR1902.pdf>

This is a link to the National Transportation Safety Board's Highway Accident Report for the Pedestrian Bridge Collapse over SW 8th Street in Miami, Fla. that is referenced in the Editorial on page 2.

### <https://www.nts.gov/investigations/AccidentReports/Pages/HAR1902.aspx>

This is a link to an NTSB webpage from which other documents related to the investigation of the FIU pedestrian bridge collapse discussed in the Editorial on page 2 can be obtained.

### <https://www.stantec.com/en/markets/transportation/bridges>

This is a link to the website for Stantec's bridge market sector. Stantec's North American bridge division provides a full complement of bridge engineering services and is the featured company in the Focus article on page 6.

### <http://parapidbridges.com>

This is a link to the Plenary Walsh Keystone Partners' website for PennDOT's Rapid Bridge Replacement project featured in a Perspective article on page 11. The multiyear, \$1.1 billion project has replaced 558 bridges.

### <https://www.youtube.com/watch?v=4uFGawmzNXM>

This is a link to a Delaware Department of Transportation time-lapse video of the construction of the Christina River Bridge in Wilmington, Del. The bridge is featured in a Project article on page xx and also is mentioned in the State article on page 16.

### <https://highways.dot.gov/bridges-and-structure/ultra-high-performance-concrete/ultra-high-performance-concrete>

This is a link to a Federal Highway Administration (FHWA) website featuring a video explaining the components and virtues of ultra-high-performance concrete (UHPC). This FHWA website also has links to websites of UHPC projects. UHPC is the subject of a Concrete Bridge Technology article on page 32.

### <http://www.aspirebridge.com/magazine/2017Spring/CBT-UHPC-GameChanging-SPG2017-Web.pdf>

This is a link to the Concrete Bridge Technology article "UHPC Is a Game-Changing Material for Bridge Producers," which appeared in the Spring 2017 issue of *ASPIRE*®. It is mentioned in the Editor's Note for the Concrete Bridge Technology article on page 32 that outlines a PCI-sponsored project to assist six precasters in developing their own UHPC mixtures.

### <https://infobridge.fhwa.dot.gov>

This is a link to the FHWA Long-Term Bridge Performance (LTBP) InfoBridge. InfoBridge is a portal to access bridge performance-related data and information. InfoBridge is highlighted in the FHWA article on page 44.

### <http://www.trb.org/main/blurb/179653.aspx>

This is a link to the downloadable version of *Design of Concrete Bridge Beams Prestressed with CFRP Systems*, National Cooperative Highway Research Program (NCHRP) Report 907. The report is mentioned in a Concrete Bridge Technology article on page 38, which focuses on methods of preventing or delaying corrosion of reinforcement.

### <http://www.trb.org/NCHRP/Blurbs/176163.aspx>

This is a link to the downloadable version of *Strand Debonding for Pretensioned Girders*, NCHRP Report 849. The report was the basis for the recently adopted revisions to the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* on debonding mentioned in the LRFD article on page 52.

### [https://www.fhwa.dot.gov/bridge/abc/docs/Blackbird-Station-Road\\_casestudy.pdf](https://www.fhwa.dot.gov/bridge/abc/docs/Blackbird-Station-Road_casestudy.pdf)

This is a link to a project case study on the use of UHPC for connections and an overlay in the replacement of Bridge 1-438 on Blackbird Station Road over Blackbird Creek in Townsend, Del. The project is mentioned in the State article on page 46.

### [https://abc-utc.fiu.edu/mc-events/abc-methods-for-delawares-all-precast-bridge-1-438/?mc\\_id=422](https://abc-utc.fiu.edu/mc-events/abc-methods-for-delawares-all-precast-bridge-1-438/?mc_id=422)

This is a link to the archived FIU ABC Center webinar on Bridge 1-438 on Blackbird Station Road over Blackbird Creek in Townsend, Del., and related information, including the UHPC overlay specifications. The project is mentioned in the State article on page 46.

## OTHER INFORMATION

### <https://www.fhwa.dot.gov/bridge/pubs/hif18046.pdf>

This is a link to a downloadable version of *Manual for Refined Analysis in Bridge Design and Evaluation* (HIF-18-046) published by the Federal Highway Administration. This manual provides guidance on performing refined analysis of bridges with guidance provided for modeling prestressed and post-tensioned concrete girder bridges. Methods and examples are included.

### <http://www.dot.state.mn.us/research/reports/2019/201930.pdf>

This is a link to a downloadable version of *Debonded Strands in Prestressed Concrete Bridge Girders* (MN/RC 2019-30), the final report of a study sponsored by the Minnesota Department of Transportation. The study gathered existing research on debonding and concerns and practices from selected state departments of transportation. The study includes design recommendations and potential material specifications to protect debonded strands.

### <http://elearning.pci.org>

This is a link to the PCI eLearning Center website, which contains online courses on precast/prestressed concrete elements and materials for the transportation and building industries. These courses are free and satisfy continuing education requirements of engineers in all 50 states.

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