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SPRING 2017
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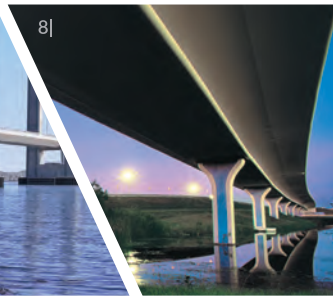
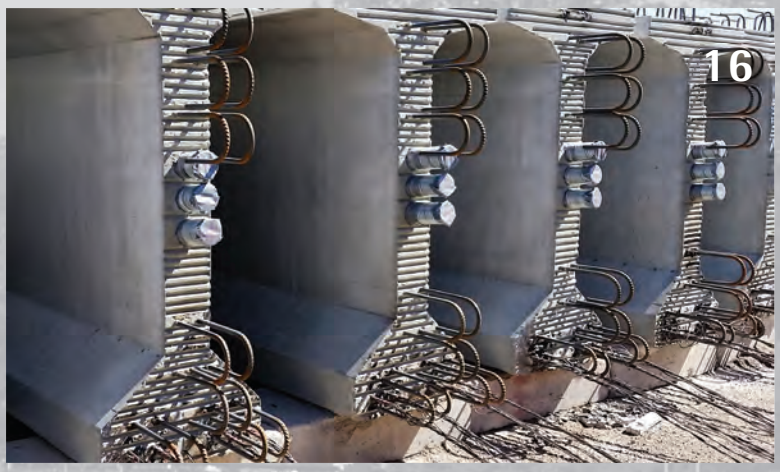
7| Sarah Mildred Long Bridge, ME, *Rendering/Under Const.*
8| Selmon Expressway, FL





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EDITORIAL

Photo: PCI.

The Engineer's Role as Advocate

William Nickas, *Editor-in-Chief*

Last year's unconventional election cycle caused me to think of the unique responsibility that we have as engineers to educate governmental leadership about how EVERY bridge contributes to the mobility of people and goods. Bridges, of course, directly impact the health of our economy. In a 2009 *ASPIRE*™ perspective article, author Andy Herrmann wrote about the ASCE *America Infrastructure Report Card*. Overall, the nation's bridges received a letter grade of "C+." In a 2017 evaluation, ASCE reported just a modest improvement for the bridge sector of our nation's assets.

Our internal industry discussions alone will not have an impact on governmental priorities. One way that awareness is raised is when a nonconstruction news entity publishes statistics showing the condition of bridges in your areas. Your community may turn to you, their trusted bridge engineer friend, to help them understand the significance of the data. As a resource, look at this great article with interactive graphics, published by the *Washington Post:* http://tinyurl.com/z3zxej7 (Note: this URL may be selected directly from the electronic version of *ASPIRE* available at www.aspirebridge.org.)

People often hear about how 130,000 of our nation's 601,000 bridges are "deficient." The public does not always understand nuanced terms, such as functional obsolescence or structurally deficient bridges. But everyone understands when a local bridge is closed or posted for lower capacity. For 50 years (1960 through 2009), the United States built an average of 9100 bridges per year. During the most recent five years, the United States has averaged fewer than 6800 new bridges per year. I hope this editorial or similar articles you read will be your call to action to help raise public awareness and return bridge-replacement construction funding to appropriate levels to improve our national economy.

We have all seen a programmatic focus on the preservation and renewal of the interstate and primary systems by federal and state infrastructure asset managers. The utilization of federal funds is tied to these highway systems. What about the condition of the local system? Many of the structures were created during the early twentieth century. When freight leaves the primary system, will there be detours and restrictions before it reaches the local consumer? Are there obstacles to the movement of emergency vehicles? What funding sources will take care of the local orphan bridges? It is all too apparent that these structures need additional investment.

In the last issue of *ASPIRE* (Winter 2017, p. 10), the perspective article by Ed Wassermann and the late Dennis Mertz explains the difference between design life and service life. Both terms are clearly important. Extending or even meeting service-life expectancy requires periodic interventions. Some bridge types require more frequent expenditures than others. In this issue of *ASPIRE* (p. 38), an article by Hank Bonstedt explores the data in the National Bridge Inventory and notes the progression of span ranges achieved by concrete bridges.

I am always pleased to see interest in public awareness of infrastructure and how the collective-transportation industry works to support our goal of a safe, mobile society moving people and goods efficiently and effectively. Likewise, it is important for engineers to share how our industry is working hard to help all stakeholders build more-resilient structures with lower life-cycle costs, all the while minimizing construction interruption to the motoring public. Let's all work to accelerate the dissemination of all available technical knowledge not only to designers everywhere, but also to the field personnel who must faithfully implement our best designs. Our goal is to arm everyone with a comprehensive library of outstanding concrete solutions.

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The $170-million Sarah Mildred Long Bridge is currently being constructed by Cianbro. Photo: Cianbro.

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For more information on the country's infrastructure grade, see the Transport Topics *article at http://tinyurl.com/zyph747*

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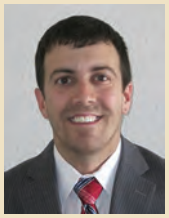

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CONCRETE CALENDAR 2017

For links to websites, email addresses, or telephone numbers for these events, go to www.aspirebridge.org and select "EVENTS."

April 4, 2017
Why UHPC for Prefabricated Bridge Element Connections? Webinar
Register at http://tinyurl.com/j2hqu7a

April 26–28, 2017
PTI Level 1 & 2 Bonded PT Field Specialist Training and Certification
Norfolk, Va.

April 30–May 3, 2017
PTI Convention 2017
Hyatt Regency Atlanta
Atlanta, Ga.

May 9, 2017
Structural Design, Detailing, and Specifying UHPC for Prefabricated Bridge Element Connections (PBEC) Webinar
Register at http://tinyurl.com/j2hqu7a

May 9–10, 2017
FDOT, ASBI, and PTI sponsored Flexible Filler Certification Training
Tallahassee, Fla.

June 4–8, 2017
International Bridge Conference
Gaylord National Resort & Convention Center
National Harbor, Md.

June 6, 2017
Construction, Inspection and Quality Assurance of UHPC Connections Webinar
Register at http://tinyurl.com/j2hqu7a

June 11–15, 2017
AASHTO Subcommittee on Bridges and Structures Annual Meeting
The Davenport Grand
Spokane, Wash.

June 12–14, 2017
fib *Symposium 2017*
Maastricht, The Netherlands

July 11, 2017
UHPC Implementation Stories Webinar
Register at http://tinyurl.com/j2hqu7a

August 6–10, 2017
AASHTO Subcommittee on Materials Annual Meeting
Sheraton Grand Phoenix
Phoenix, Ariz.

August 21–22, 2017
2017 New York City Bridge Conference
Marriott New York East Side
New York City, N.Y.

August 29–30, 2017
PCA Fall Congress
InterContinental Chicago Magnificent Mile
Chicago, Ill.

September 6–8, 2017
2017 Western Bridge Engineers' Seminar
Portland Marriott Waterfront
Portland, Ore.

October 2–4, 2017
3rd International Symposium on Ultra-High Performance Fibre-Reinforced Concrete
Montpellier, France

October 4–6, 2017
2017 PTI Committee Days
CasaMagna Marriott Cancun Resort
Cancun, Mexico

October 4–7, 2017
PCI Committee Days 2017
Loews Chicago O'Hare
Rosemont, Il.

On page 12 of the Winter 2017 issue of ASPIRE, *we incorrectly listed the pier replacement design engineer for the Long Key Bridge Pier Replacement. The correct firm is URS (AECOM). We regret this error.*

LETTER TO THE EDITOR

Dear Editor,

ASPIRE *is really good. I think I have every single e-version on my laptop. I am constantly telling our folks, "Let's be proud of our accomplishments, big and small, and get our finished work products presented/published."*

Dan Shiosaka

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DELIVERING CONCRETE INNOVATIONS

Cianbro has adapted to new delivery methods, technologies, and design techniques to construct complicated projects on tight schedules and budgets

by Craig A. Shutt

Cianbro Corporation has built a reputation for taking on challenging projects and producing cost-efficient bridges that are completed on time. As new delivery methods have developed, the general contractor has thrived, becoming well known for its work in several specific types of concrete bridge projects that often provide signature designs.

"Cianbro is a one-hundred-percent employee-owned company, and that commitment aids our drive to deliver on time, with high quality, and on budget," says Kaven Philbrook, senior project manager for infrastructure at the Pittsfield, Maine-based company. "We have become known in the industry for undertaking very unique, difficult projects where schedule is of the utmost importance."

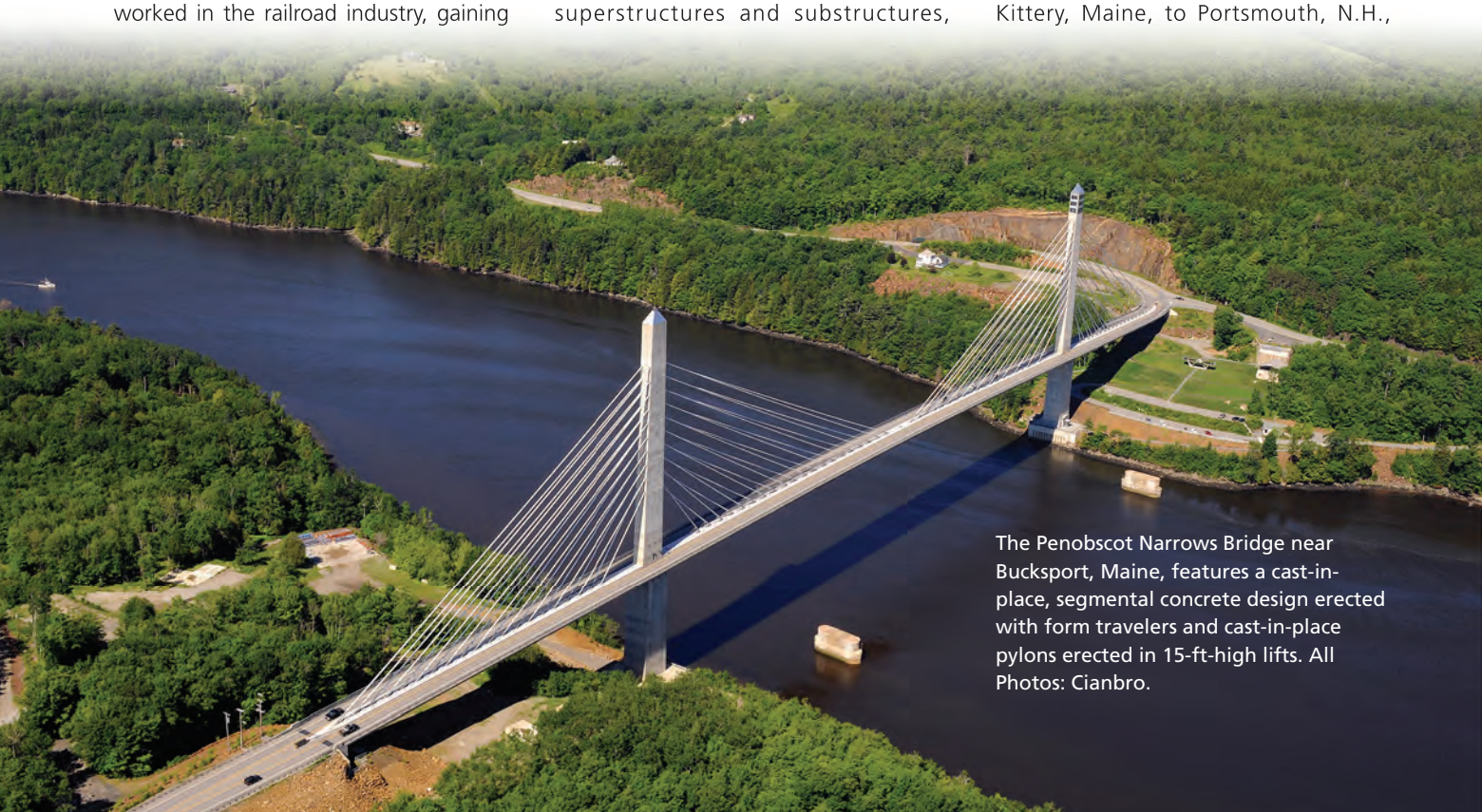
Founded in 1949, Cianbro has long worked in the railroad industry, gaining experience with a variety of accelerated bridge construction (ABC) techniques as well as skill in constructing efficient movable bridges. Its work with concrete bridges has led to expertise with such specialized structure types as segmental bridges, cable-stayed designs, and arched substructures. "We have become known for doing these projects from Florida to Maine," says Philbrook.

Segmental Designs

Segmental concrete bridges have become a key part of the company's work and offer significant benefits in the right circumstances. "We're very selective about which segmental projects we take on," Philbrook says. "If the project presents unique challenges, especially in having aggressive schedules, we are very competitive."

Concrete segmental designs can provide benefits to designs for both superstructures and substructures, says Brenda Nichols, Cianbro's senior design engineer. Her presentation at the 2016 Construction Practices Seminar, sponsored by the American Segmental Bridge Institute (ASBI) and featured in the Fall 2016 issue of *ASPIRE*™, outlined benefits of concrete segmental substructure components, such as footings, pier caps, and column units. Benefits accrue similarly for segmental superstructure components, she noted, including speed of erection, reduced user costs, better quality and durability, and improved safety.

Philbrook is currently working on a major segmental project, the $170-million Sarah Mildred Long Bridge, a joint venture between New Hampshire and Maine to replace what was reported to be the number-one red-listed bridge in New Hampshire. The new two-level precast concrete segmental box-girder structure connects Kittery, Maine, to Portsmouth, N.H.,



The Penobscot Narrows Bridge near Bucksport, Maine, features a cast-in-place, segmental concrete design erected with form travelers and cast-in-place pylons erected in 15-ft-high lifts. All Photos: Cianbro.

Precast concrete tubs for forming the footings on the Sarah Mildred Long Bridge provide both short-term and long-term benefits.

across the Piscataqua River. When it opens later this year, the upper level will carry vehicles while the lower level will provide rail access. It will include a 300-ft-long movable lift span supported by four 194-ft-tall concrete lift towers.

"This is the first bridge in the world to have the towers constructed this way," Philbrook says. Cianbro is working through a construction manager/general contractor (CM/GC) contract and chose to produce the 100-ton, match-cast tower segments in this format due to the tight timetable. "Using precast concrete shortened the schedule by months."

The company has produced cast-in-place concrete towers for cable-stayed projects and originally planned to do these similarly, Nichols says. But the team realized that precast concrete could save time and expense. Casting each tower on site would have added four months to the bridge schedule's critical path, she explains.

Alternative Delivery Methods

The project's CM/GC delivery method plays to Cianbro's strengths, Philbrook notes. "We do very well with alternative delivery methods that encourage more collaboration and innovative thinking." Cianbro was selected as the construction manager for the project and worked closely with both states and the FIGG Design Group to devise the best design. The company then won the general-contractor portion and worked with FIGG to optimize scheduling and constructability issues.

'We do very well with alternative delivery methods that encourage more collaboration and innovative thinking.'

Cianbro excels at CM/GC projects, Philbrook says. In that format, the design team works for the owner and focuses on outlining all issues to avoid budget surprises. "We identify all potential risks and put aside funds to cover them," he explains. "If they don't happen, we all save money, and if they do happen, we've already identified them and share the costs." The format produces a more accurate cost, as the contractor isn't factoring in funds for potential risks that aren't being shared or don't arise.

The Sarah Mildred Long Bridge, for instance, uses 10-ft-diameter drilled shafts, but Cianbro wasn't certain how much slope there would be to the ledge into which they would be driven. The contract called for a higher payment if the slope turned out to be higher than a certain percentage. "That way we share the cost only if the issue arises," Philbrook explains.

Cianbro produced the Penobscot Narrows Bridge under an owner-facilitated design-build (OFDB) contract, in which the firm works directly for the owner. The company's bid was selected by Maine Department of Transportation officials as providing the best combination of schedule, cost, and team qualifications. The cable-stayed bridge over the waterway near Bucksport, Maine, features a cast-in-place, segmental concrete design.

The project arose after an initial plan to repair the existing bridge found the cables so deteriorated that the bridge had to be immediately downgraded to a 12-ton load limit. With the nearest detour more than 50 miles away, Cianbro was given 39 months to design and build the new structure.

The $170-million Sarah Mildred Long Bridge currently being constructed includes an upper level for vehicles and a lower level for rail access. The precast concrete segmental box-girder structure features a movable lift span supported by four 194-ft-tall concrete lift towers.

The Humpback Bridge over the Boundary Channel on the George Washington Parkway near Washington, D.C., consists of a single span with segmental precast concrete arches.

"Our goal was to eliminate the time involved with the permitting process for putting piers into the water by creating a 1161-ft-long main span supported by the cables," he says. Cast-in-place concrete segments were erected over the water with a form traveler and cast-in-place concrete pylons were constructed in 15-ft-high lifts. The project proved so successful that it received an ASBI Award of Excellence.

New delivery methods are gaining popularity, Philbrook says. "We see them happening more today as states see the benefits." Since its work began on the Sarah Mildred Long Bridge, he adds, the firm has gained two more CM/GC projects in New England.

Arched Designs Grow

Cianbro also has gained notice for its work on concrete-arch bridges, creating several dramatic structures that retain the legacy of older bridges while offering modern building techniques and materials. "Typically, we stand out on arched designs due to our in-house construction-engineering capabilities and the innovative ways we use to erect the arches," Philbrook says. Those methods include tie-backs and skylines. "We used all kinds of means and methods, designed in-house, to make us very competitive in meeting schedules."

'We stand out on arched designs due to our in-house construction engineering capabilities and the innovative ways we find to erect the arches.'

Segmental precast concrete arches were designed for the Humpback Bridge over the Boundary Channel on the George Washington Parkway near Washington, D.C. The single-span bridge, owned by the National Park Service, features half-arches made up of smaller segments. The arch pieces were match-cast in a horizontal position, with all seven segments for each half-arch cast in one setup, alternating segments. Each half-arch was cast in less than 1 week. The outer arches were cast with a façade using stonework saved from the original bridge. The half-arches were joined with cast-in-place concrete closure pours.

Aesthetic touches such as reuse of stone and arched designs often result from communities wanting to retain a former appearance. Cianbro stays in touch with community concerns by gathering feedback as soon as possible. "We see a lot more input desired on all types of bridges, not just signature ones," Philbrook says. "The community wants the bridge to fit the community on every site, and people are making their concerns known. We're very proactive in encouraging community involvement to gain their support."

That was a key part of the Sarah Mildred Long Bridge's design. "We worked with Maine officials, who were very focused on getting community involvement in the design and scheduling. We've had a number of meetings to address the design and bridge shape to meet their concerns."

Cianbro's Growth

Cianbro was founded after World War II when Carl Cianchette revived the bridge-building firm begun by his father, Ralph Cianchette, in the mid-1930s. Three of Ralph Cianchette's other five sons soon joined, and the business was incorporated in 1949. It grew steadily during the next 68 years, branching out to disciplines that include paper-mill maintenance, steel fabrication, hydroelectric dam repairs, ship upgrades, and more.

By 1979, the company had begun a successful expansion of its heavy-construction operations into the southern New England and mid-Atlantic regions. The acquisition of Starcon International Inc. in 2010 launched Cianbro into the $12-billion refining and petrochemical service business with a nationwide presence.

In 1965, the company established a profit-sharing program for qualified employees, which led in 1977 to the company offering team members the opportunity to buy stock in the company. By the early 2000s, Cianbro was transitioning to a 100% employee-owned firm. In 2014, the National Center for Employee Ownership ranked Cianbro 13th among the largest 100% employee-owned firms in the United States. Today, Cianbro is one of the country's largest open-shop contractors, operating in more than 40 states. It employs more than 4000 people.

Concrete tolerances were tight (1/4 in.) on the piers used for the Brightman Street Bascule Bridge over the Taunton River between Fall River and Somerset, Mass. Cianbro also employed a full-time, on-site quality-control team to oversee concrete mixture proportions.

On some projects, including the Humpback Bridge over the Boundary Channel, Cianbro subcontracted the concrete fabrication. It is precasting components for the Long bridge, because the site offers no space for staging and delivering components from an outside plant. "We look at how it can be done most efficiently," Philbrook says.

Concrete Innovations

Because it operates a concrete facility in Pittsfield, Maine, Cianbro stays current with product trends, taking advantage of new concepts, especially as bridge owners look to push 75-year design lives closer to 100 years. "We're using high-performance concrete with corrosion resistance and high strength more often," Philbrook explains. "It's a case-by-case basis as to how we achieve the longevity goals the owner desires, but we are always looking for ways to provide higher quality, better corrosion resistance, and lower permeability."

Concrete strength in general is higher today, he adds. "We used to typically get 6500- to 7500-psi mixtures, but now it's often up to 10,000 psi. Corrosion inhibitors are becoming more numerous and widely used to bolster those properties. Some states also are looking at using epoxy coating on all reinforcing steel, with some going to galvanized or stainless-steel options."

'We used to typically get 6500- to 7500-psi mixtures, but now it's often up to 10,000 psi.'

Concrete tolerances are tightening, too, as can be seen with the company's work on the Brightman Street Bascule Bridge over the Taunton River between Fall River and Somerset, Mass. Precision was critical for the concrete bascule piers to ensure lifting equipment at the top performed flawlessly. The concrete needed to meet tolerances within 1/4 in., allowing the machinery's grout pads to cover the rest.

Precise concrete mixtures were used to cast the counterweights and lightweight concrete fill for the grid deck. Cianbro used a full-time, on-site quality-control team to oversee mixture proportions. "We ensured the concrete was mixed precisely, with every truckload tested for air entrainment, slump, water-cement ratio, and other properties," Philbrook says. "Everything was double-double checked."

On-site safety also is double-checked, he notes. At the Sarah Mildred Long Bridge in early January, those systems led to 810 days with no injuries. "Our program starts at the top but it's very much driven from the bottom," he says. At the top, it includes creating work plans that emphasize identifying and engineering out all hazards and building safe access roads and sites. Safety meetings are held at regular intervals during the construction process as well.

The bottom-up drive comes from the Cianbro accident-prevention process in which each work-site employee submits two forms per month noting an improvement for the site or flagging a potential hazard. "We take immediate action and then see if there is a way to avoid them on future projects."

Cianbro takes its interest in employee needs a step farther with the Cianbro Institute, which helps train new personnel and expand the skills of existing employees. The program includes classes as well as visits to project sites. For instance, the program offers five levels of training for riggers, with some project riggers making presentations and students visiting sites to do some rigging.

"We encourage employees to learn new skills and improve their value," Philbrook says. As an employee-owned company, it benefits the company to have its owners gaining more expertise. "When our employees upgrade their skill sets, it helps all of us by making them more valuable."

Those skills will come in handy as Cianbro continues to look for innovative ways to meet new challenges that arise with delivering their complicated projects on-time and on-budget.

EDITOR'S NOTE

The Penobscot Narrows Bridge was featured in the Winter 2007 issue of ASPIRE™*, and the Humpback Bridge over the Boundary Channel was featured in the Winter 2010 issue.*

PERSPECTIVE

A Different Approach to Risk Allocation on Construction Sites

OSHA's crystalline silica rule requires it

by Michael R. Peelish, Law Office of Adele L. Abrams PC

Respirable crystalline silica dust is different from all other contaminants located on a jobsite. There is no other material that makes up so much of the earth's crust and is found in so many construction materials and products. It also can be released in respirable-sized particles by many different tasks. Silica dust is pervasive in how it permeates the jobsite, and how it affects workers of different employers.

When a general contractor uses multiple subcontractors to construct commercial bridges, buildings, warehouses, or outdoor structures, how do the parties allocate the risk of silica dust exposure for each company's employees? This is a significant issue when multiple contractors occupy the same worksite. Some contractors may generate high levels of silica dust from a variety of activities, while others may generate no contributing respirable silica dust themselves, but work downwind from other contractors who create exposures above legal limits for workers.

The new Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) is 50 $\mu g/m^3$ for an eight-hour time-weighted average, which is only 20% of the previous limit. The new exposure limitations (OSHA 29 CFR 1926.1153), along with the rest of the silica rule's provisions for training, exposure monitoring, and medical surveillance, are scheduled to take effect for the construction sector on June 23, 2017. OSHA can issue citations to the general contractor, the creating contractor (the entity that generates high levels of silica dust), the exposing contractor (the employer whose workers are exposed above the PEL), and the controlling contractor (the party who, by practice or by contractual agreement, is responsible for eliminating this hazard from the workplace). Often, OSHA will consider contract documents among various employers at a shared worksite in determining who has primary responsibility for hazard mitigation, and this can be reflected in how citations are issued in terms of negligence.

A rigger prepares for installation of a precast concrete element in a common jobsite area. All Photos: Law Office of Adele L. Abrams PC.

The typical approach of being handed a consensus document and asked to sign it does not allocate risk adequately. In our review of several consensus documents, the contract language addressing risk allocation concerning silica dust is not sufficient. These consensus documents can create a Tammany Hall–like ring of employers pointing their fingers at the next employer and not willing to take any claim of responsibility for dust overexposure.

Unfortunately, if OSHA visits a multi-employer jobsite and finds overexposures because the parties have not adequately addressed the responsibility of controlling silica dust, it normally will cite multiple parties and let the courts sort it out. There can also be ripple effects, because once a contractor is documented to have exposed other companies' workers to hazardous levels of silica dust, third-party tort actions for personal injury or wrongful death can follow. To avoid this scenario, controlling silica dust below the PEL is the solution the parties should try to achieve.

The web of contracts on a jobsite in the precast concrete industry might go something like this: The general contractor has a contract with the precast concrete producer, which has a contract with the shipping company to deliver the concrete components, and has another contract with the erector subcontractor to install the concrete components, and yet another contract with a patching and grouting company to make sure every concrete component is acceptably installed. In short, the general contractor will have contracts with as many subcontractors of various

An equipment operator works in a common jobsite area.

trades as are necessary to complete the job. The building owner will have its engineers on the jobsite to ensure the project goes according to plan. Woven into these relationships will be the rental equipment company personnel operating and maintaining the cranes, high lifts, fork lifts, excavators, and crushers, just to name a few.

How then should the parties on a jobsite approach risk allocation with multiple parties involved, many of which will generate silica dust and all of which could have employees exposed? By way of example, let's take the relationship between a general contractor and the precast concrete producer and work through it. Keep in mind that the precast concrete producer will have its own contract with its subcontractors.

First, the contractual language must ensure that all parties comply with the new OSHA silica rule that directly affects the jobsite by having a written exposure control plan and a competent person present at the jobsite to implement the plan. To achieve this, the contract must contain general language about complying with all federal, state, and worksite occupational safety and health rules. That language may be sufficient to ensure that the silica written exposure control plan and competent person requirements are met.

Next, even with exposure control plans and competent persons on the jobsite, the jobsite situations can become murky without contract language to allocate risk. For instance, take the situation wherein a subcontractor's worker is operating a rented high lift that has an exhaust pipe located on the undercarriage of the equipment on a dry roadway, and where a rigger is preparing to offload a precast concrete component. Who is responsible for controlling the silica dust generated in this common area? By the way, the worker operating the high lift was exposed above the OSHA PEL of 50 µg/m^3 and the rigger was exposed above the action level of 25 µg/m^3.

The contracting parties must allocate risk at the jobsite according to which party has authority to dictate the work activities to control silica dust. In the situation described, there were six or more subcontractors in the general area where these two workers were located. Therefore, the general contractor and its subcontractors must identify which party has the responsibility to control the generation of silica dust. In my opinion, the practical approach is to include language that places the responsibility squarely on the party that has the appropriate authority to control common-area silica dust—the general contractor. Here's an example of the type of language that should be used:

"The General Contractor shall be responsible for controlling dust (which may include respirable crystalline silica) on a Construction Project regardless of its source(s) including, but not limited to, wind-blown onto the site, generated by truck and equipment travel regardless of who is operating the truck or equipment, or generated by other parties. The Subcontractor shall only be responsible for control of dust generated by the performance of its work activities or the work of its subcontractors, such as cutting, sawing, drilling, grinding, patching, or altering the precast concrete components."

In addition, the general contractor must ensure that all subcontractors are conducting their work in a manner that minimizes silica dust generation by implementing written exposure control plans and having a competent person on the jobsite.

In summary, risk allocation can be handled by applying a simple approach:

- Ensure that all parties subject to the OSHA silica rule comply with its mandates of maintaining a written exposure control plan and having a competent person on the jobsite.
- Identify which party has the authority to dictate work to control the silica dust exposure and ensure that the contract language places responsibility and accountability clearly on that party.
- Ensure that the contract language is enforced.

ROCHESTER FAST 4 ON VT 73

USING INNOVATIVE BRIDGE CONSTRUCTION TO EXPEDITE PROJECT DELIVERY

by Jennifer Fitch, Vermont Agency of Transportation, and
Scott Burbank and Greg Goodrich, Vanasse Hangen Brustlin Inc.

The town of Rochester, Vt., sits on the edge of the Green Mountain National Forest, characterized by its picturesque village center, rural farmland, and small population of 1100. In 2011, it was devastated in the aftermath of Tropical Storm Irene. The damage included the collapse of two structures—Bridges 13 and 19 on Vermont Route 73 (VT 73)—leaving many local residents stranded. While immediate measures were taken to reopen the roadway and restore mobility, only temporary structures were available on such short notice.

Bridge 13 on VT 73 near Rochester, Vt., following Tropical Storm Irene. Photo: Vermont Agency of Transportation.

Prior to the storm, Bridges 13 and 19 were considered in fair condition and, therefore, had not been programmed for replacement. Initially, this made it difficult to prioritize their repair among other infrastructure projects. There was also the matter of how to allocate scarce funding. Luckily, these structures were eligible for emergency relief funding, but this also placed significant time restrictions on the design and reconstruction of both structures. In addition, Bridges 15 and 16, which were also located on VT 73, had been previously programmed for replacement. Because they were entering the project definition stage at the same time, there was an opportunity to leverage a consistent and coordinated approach across all four projects. This meant that Bridges 15 and 16 would need to adhere to the same condensed schedule as the other two emergency-relief projects.

To expedite project delivery, all four projects were assigned to the Vermont Agency of Transportation's (VTrans's) newly established Accelerated Bridge Program (ABP). In addition, all projects were assigned to a single VTrans project manager and the same design consultant to ensure heightened coordination and consistency. Given the substandard bridge widths, narrow roadway, restrictive right-of-way, and historic dwellings near the structures, phased construction and temporary bridges were not feasible for three of the four structures. Instead, these structures would need to be replaced innovatively using prefabricated bridge elements and systems (PBES) and short-term closures to minimize project impacts and meet aggressive milestone dates. Bridge 19, a 127-ft-long, single-span, steel-girder bridge, was considered "conventional" with traditional design details and

profile

ROCHESTER FAST 4 ON VT 73 / ROCHESTER, VERMONT

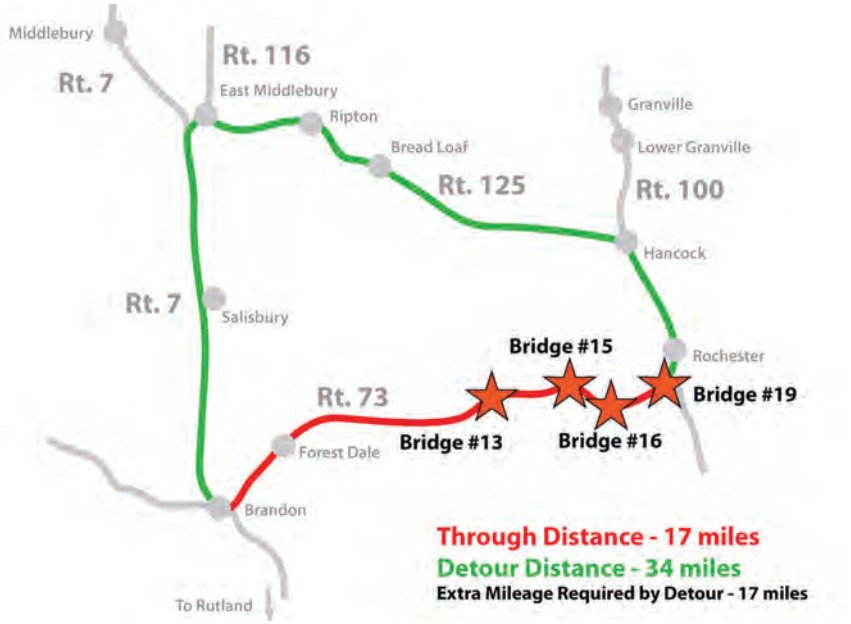
PROJECT MANAGER: Vermont Agency of Transportation, Montpelier, Vt.

BRIDGE DESIGN ENGINEER: Vanasse Hangen Brustlin Inc., South Burlington, Vt.

PRIME CONTRACTOR: WM Schultz Construction, Ballston Spa, N.Y.

PRECASTER: Joseph P. Carrara and Sons Inc., Middlebury, Vt.—a PCI-certified producer

POST-TENSIONING CONTRACTOR: Joseph P. Carrara and Sons Inc., Middlebury, Vt.



Rochester Fast 4 on VT 73 project location map. Photo: Vanasse Hangen Brustlin Inc.

permitted an entire construction season for erection, and thus will not be described in this article.

One of the primary goals was to deliver all projects in a single construction season, which was a daunting task given Vermont's truncated construction season from May to October. In addition, state and local detour routes are scarce to nonexistent in this part of Vermont, resulting in a lengthy 34-mile detour from end to end.

Given these two factors, along with a community hesitant to road closures following Tropical Storm Irene, all closures were limited to long weekends for two of the bridges and 14 days for the third, a significant deviation from the ABP's standard bridge closure period of 21 to 28 days. This required bridge designers to focus on means and methods throughout the design phase to facilitate rapid construction. All projects were combined into a single contract to ensure coordinated replacement with a single contractor.

Design and Construction

Each of the bridge designs, when considering complexity alone, is relatively straightforward by its nature. However, there are several notable features and facets of the three concrete bridge designs discussed in this article that distinguish the overall project, because of site constraints and the need for rapid replacement.

Bridges 15 and 16

Bridges 15 and 16 share similar site characteristics and were designed to be constructed during long-weekend closures (Thursday evening through early Monday morning for Bridge 15, and Friday evening through early Monday morning for Bridge 16). This allowed both structures to use similar design details and specifications where practical. Using a more coordinated design approach provided the fabricators and contractors an opportunity to gain familiarity with the design and detailing, which increased the likelihood for successful bridge replacements within the identified bridge closure periods.

Bridges 15 and 16 are viewed in many ways as "sister structures" because the existing bridges were of similar length, width, and construction (both were cast-in-place, reinforced concrete girder bridges), which lent them to being designed using similar details. Both replacement bridges feature 28-in.-deep precast, prestressed concrete Northeast Extreme Tee (NEXT) beam superstructures bearing on precast concrete abutments, which were each supported on a single row of steel H-piles.

Bridge 15 is a 64-ft-long, single-span bridge with a 32 ft curb-to-curb width, and Bridge 16 is a 58-ft-long, single-span bridge with a 27 ft curb-to-curb width. The longer span lengths, as compared with the existing span lengths, not only accommodated increased hydraulic capacity and future resiliency, but also allowed the pile foundations to be installed behind the existing substructures, such that the installation could be completed prior to the bridge-closure period. Each of the structures also utilized precast concrete approach slabs that bear on precast concrete curtain walls previously cast onto the NEXT beams during fabrication. Utilizing the precast concrete approach slabs also allowed for simplified design and construction of the abutments by shielding them from horizontal earth surcharges. The large

STATE OF VERMONT, OWNER

BRIDGE DESCRIPTIONS: Bridges 15 and 16: Single-span pretensioned concrete Northeast Extreme Tee beams with precast concrete curtain wall; Bridge 13: Open-bottom arch with a cast-in-place concrete subfooting with a precast concrete pedestal wall and concrete arch

STRUCTURAL COMPONENTS: Bridge 16: Precast, post-tensioned concrete abutments; pretensioned concrete Northeast Extreme Tee beams; and precast concrete approach slabs. Due to weight of the precast superstructure, the Northeast Extreme Tee beams required launching beams during erection. Bridge 15: Precast, post-tensioned concrete abutments; pretensioned concrete Northeast Extreme Tee beams with a precast composite concrete combination railing; and precast concrete approach slabs. Bridge 13: Open-bottom concrete arch with a cast-in-place concrete subfooting with a precast concrete pedestal wall.

BRIDGE CONSTRUCTION COST: $1,196,400 (Bridge 16); $1,119,835 (Bridge 15); $1,478,646 (Bridge 13).

AWARDS: 2015 Vermont ACEC Grand Award

Concrete curtain walls were precast on each end of NEXT beams for Bridges 15 and 16. Photo: Vanasse Hangen Brustlin Inc.

Precast concrete flare for historic rail. Photo: Vanasse Hangen Brustlin Inc.

semi-integral curtain walls cast onto the superstructure also allowed the bridges to be designed as a "strut," thereby mobilizing earth pressure, where needed, to resist longitudinal forces imparted on the superstructure instead of resisting the forces solely by the substructure, further reducing the demand on the pile groups.

Other notable features of the bridge designs included casting additional precast concrete elements onto the NEXT beams during fabrication to reduce the time frame for the superstructure installation. Features included

- a flared overhang at the end of one of the Bridge 15 NEXT beams to accommodate truck turning movements at the inside of the 90-degree curve,
- decorative concrete bridge rail parapets for Bridge 15 to meet historic requirements, and concrete brush curbs for Bridge 16.

Bridge 13

On the surface, Bridge 13 over Brandon Brook is simply a precast concrete culvert; however, there were several challenges specific to the site that made the design unique. The most notable feature of the structure is the sharp 56-degree skew of the waterway crossing relative to the roadway. This complicated the design, particularly considering the allowable two-week closure for installation. In an ideal situation, the roadway would remain open to traffic using phased construction to replace the temporary corrugated metal pipe installed after Tropical Storm Irene. In order to maintain traffic through the project site, however, the 28-ft-long span of the proposed structure, when coupled with the skew of the crossing, made it prohibitive to use phased construction while working within the existing right-of-way. Therefore, a road closure was necessary to construct the new culvert.

Also adding to the complexity of the design were the topography of the site and the steep 11.5% gradient of Brandon Brook. To assist with the selection of the preferred structure type, several fabricators were consulted concerning the longitudinal grade, site constraints, and ease of construction. Based on feedback, the grade of a new precast concrete culvert was limited to 5% along the length of the structure. The gradient of the brook more than doubled this allowable slope of the culvert. Therefore, the structure was placed on an oversized pedestal that varied in depth along the length to account for the 6% difference in the allowable structure grade in comparison to the actual gradient of the brook. Initially the footings were going to be "stepped" to help minimize the height of the pedestals. However, it was determined that this would complicate construction and add time to the construction duration. To simplify constructability, a constant-height, oversized precast concrete pedestal was designed, allowing the footing to be placed on a constant grade for the full length of the structure.

Completed Bridge 13 on VT 73 near Rochester, Vt. Photo: Vanasse Hangen Brustlin Inc.

Conclusion

All three concrete bridges were completed ahead of schedule, allowing the contractor to receive full incentive payment. The successful completion of these projects confirms that accelerated bridge construction projects with short closure durations can be effectively developed and executed with proper planning, design, support, public outreach, and contractor coordination. Furthermore, successful accelerated bridge construction projects, where applicable, are a benefit to their communities, the agency, and the public at large as they reduce impacts on natural and cultural resources, significantly decrease the roadway closure duration, and provide safer bridges with longer service lives because the PBES are manufactured in a controlled setting at a fabrication plant.

Jennifer Fitch is a project manager with the Vermont Agency of Transportation in Montpelier, Vt. Scott Burbank is a project manager with Vanasse Hangen Brustlin Inc. in South Burlington, Vt., and Greg Goodrich is a project manager with Vanasse Hangen Brustlin Inc. in Bedford, N.H.

THE ESTRELLA UNDERPASS AT GRAND AVENUE

by John Lange, Stanley Consultants

State Route (SR) 303L is a 40-mile-long new freeway in the western and northwestern portions of the greater Phoenix, Ariz., metropolitan area. Originally known as the Estrella Freeway, it opened in 1992 as a two-lane freeway. Growth and future traffic projections have driven the need to expand SR 303L to an ultimate configuration of six lanes in each direction. This growth in the Phoenix metro area has had a significant impact on bridge design and construction methodology. Bridge widening on existing freeways and over busy urban arterials often requires bridge engineers to explore innovative designs to maintain traffic during major bridge construction activities.

The Estrella Underpass at Grand Avenue bridge carries SR 303L over U.S. 60 (Grand Avenue) and the Burlington Northern Santa Fe (BNSF) Railway. The challenge of maintaining traffic on U.S. 60 during construction was complicated by the limited detour options. High traffic volumes of 24,000 and 12,700 vehicles per day on U.S. 60 and SR 303L, respectively, precluded extended closures with off-site detours. Consequently, the final design of this bridge was driven primarily by the need to maintain both vehicular and railway traffic through this interchange.

Innovating from the Start

The original project design concept report proposed widening on both sides of the existing bridge. This approach created significant constructability and access issues. Large excavations for the deep spread footings impacted U.S. 60, the BNSF Railway, and underground utilities. It also resulted in aesthetic inconsistencies among the bridge substructure elements.

Partially completed bridge ready for drop-in girders over railroad. Construction was paused multiple times each day for railroad traffic to pass through the site. Photo: Haydon Building Corp.

profile

ESTRELLA UNDERPASS AT GRAND AVENUE / SURPRISE, ARIZONA

BRIDGE DESIGN ENGINEER: Stanley Consultants, Phoenix, Ariz.

PRIME CONTRACTOR: Haydon Building Corp., Phoenix, Ariz.

PRECASTER: TPAC, Phoenix, Ariz.—a PCI-certified producer

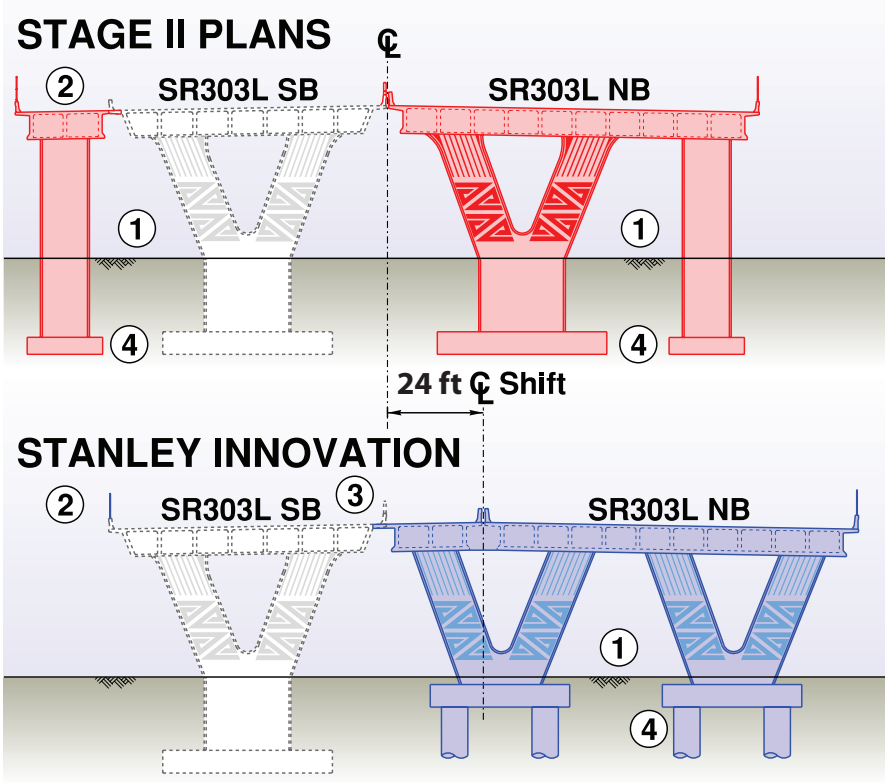
POST-TENSIONING CONTRACTOR: Dywidag Systems International, Long Beach, Calif.

OTHER MATERIAL SUPPLIERS: Reinforcing Bar Producer: Nucor Steel LLC, Kingman, Ariz.; Reinforcing Bar Fabricator: CMC Rebar, Mesa, Ariz.; and Reinforcing Bar Installation: Endo Steel, Gilbert, Ariz.

AWARDS: 2016 CRSI Honors Award and 2016 American Council of Engineering Companies (ACEC) Grand Award

During the proposal phase, the winning proposal was the only team of the twelve competing teams to propose shifting the freeway construction centerline 24 ft east and replacing spread footings with drilled shafts. This innovative concept provided the following advantages (items are keyed to figure to the right):

1. Inconsistent bridge piers were made uniform so aesthetic treatments were a natural extension of the existing bridge.
2. The southbound widening was eliminated, improving construction phasing and access.
3. All new construction was on the east side with only one interface between new and existing bridges.
4. Drilled-shaft foundations reduced the excavation footprint and eliminated associated conflicts.



Project proposal graphic illustrating the constructibility and aesthetic benefits resulting from shifting the roadway alignment 24 ft to the east. Figure: Stanley Consultants.

A Hybrid Option

The existing Estrella Underpass Bridge was constructed in 2000. The bridge is a four-span, 536-ft-long, cast-in-place (CIP), post-tensioned concrete box-girder superstructure with custom Y-shaped columns and integral piers. The structure depth is 7 ft 4 in. and it has a span arrangement of 105, 194, 118, and 114 ft with a precast concrete drop-in span over the BNSF Railway. The project widened the existing bridge about 2½ times its original width, from an out-to-out width of 73 ft 8 in. to 197 ft 1 in. A conventional approach would have been to widen the bridge using an identical CIP post-tensioned concrete superstructure because the proximity of the railroad tracks created ample vertical clearance for falsework over U.S. 60 traffic. In addition, the length of span 2 exceeded the capabilities of pretensioned precast concrete American Association of State Highway and Transportation Officials (AASHTO) girders used in the Phoenix area.

Working with the prime contractor, an improved bridge-widening method was developed that combined AASHTO precast concrete girders with CIP concrete pier tables. Pier locations, span arrangements, and joint locations were all dictated by the existing bridge configuration. CIP concrete was used near and over the piers where demand for structural compatibility was greater. This method eliminated large portions of falsework—most important, falsework over U.S. 60. The two structure types (CIP and precast concrete) were spliced and post-tensioned to provide continuity and comparable structural behavior to the existing bridge. Spliced connections between CIP and precast concrete elements were located where dead load moments were low and where shoring towers could be placed without affecting U.S. 60.

Precast Opens the Way

A critical project requirement was maintenance of traffic on U.S. 60 during bridge construction. CIP construction on falsework over traffic is invariably disruptive to traffic below. At span 2 and over U.S. 60, 120-ft-long precast, pretensioned concrete girders were spliced with 37-ft-long CIP pier tables. Prior to post-tensioning the superstructure, the precast, pretensioned concrete girders were temporarily supported on shoring towers. This created an available clear opening of almost 100 ft for U.S. 60

ARIZONA DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: 536-ft-long, four-span, post-tensioned superstructure combining AASHTO precast concrete girders with cast-in-place concrete pier tables on integral Y-shaped piers

STRUCTURAL COMPONENTS: Twenty 60-ft-deep, 36-in.-diameter drilled shafts in a double row at each abutment; four 70-ft-deep, 96-in.-diameter drilled shafts at each pier line; cast-in-place (CIP) Y-shaped piers, pier tables, and abutments; and 56 AASHTO Type Super VI precast concrete girders with a 9-in.-thick cast-in-place concrete deck. Frame A is 316 ft long and comprises spans 1 and 2 plus a 20-ft 3-in. CIP beam ledge at pier 2 cantilevered into span 3. In frame A, three post-tensioning tendons were used per web with a total jacking force of 32,605 kip applied at hinge 1. Frame B is 123 ft long and comprises span 4 plus a 12-ft 3-in. CIP beam ledge at pier 3 cantilevered into span 3. In frame B, two post-tensioning tendons were used per web with a total jacking force of 19,685 kip applied at hinge 2.

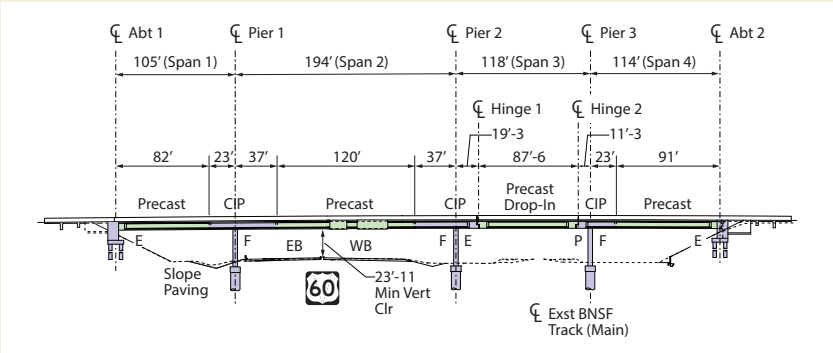
BRIDGE CONSTRUCTION COST: $7,300,000 (approximately $110.28/ft^2)

Completed piers 2 and 3 showing Y-shaped columns and the interface of the cast-in-place concrete pier tables with the precast concrete girders. Photo: Stanley Consultants.

Span 2 Precast Concrete Girder Data

$f_c^{'}$ = 6.5 ksi
$f_{ci}^{'}$ = 5.25 ksi
Strands = Grade 270, low relaxation

Number of strands = 28 (straight)
Prestressing force = 1230 kip
Length = 120 ft



Elevation view of bridge depicting span arrangement and orientation of precast and cast-in-place concrete segments. Figure: Stanley Consultants.

traffic. This large opening, with high vertical clearance, easily accommodated two lanes of traffic in each direction plus a turn lane. This solution improved public safety, provided flexibility during construction, and permitted traffic shifts to accommodate construction phasing.

To provide a structure similar in depth to the existing bridge, 6-ft 6-in.-deep AASHTO Type Super VI girders were used, spaced at 9 ft on center. These deep girders, combined with the short interim span lengths (span between shoring towers prior to post-tensioning), allowed for minimal pretensioning to accommodate the interim construction loads. All precast concrete girders were designed for two-stage stressing: an initial pretensioning for dead loads, and post-tensioning on top of pretensioning for final loads. It was desirable to minimize initial camber in the precast concrete girders to allow for the additional camber resulting from the second-stage post-tensioning and to control screed grades. The girders utilized only 0.6-in.-diameter straight strands to carry the self-weight of the girder, the deck concrete while fresh, and a nominal construction load. Harped strands could not be used due to the draped post-tensioning (PT) ducts in the girder webs. After concrete placement for the deck, the minimal initial pretensioning produced about 0.5 in. of upward camber in the girder prior to post-tensioning.

Erection of the precast concrete girders coincided with the construction of the CIP box-girder webs. This simultaneous construction reduced overall construction time and ensured proper alignment of the PT ducts. A 2-ft-wide closure pour was provided between the ends of the precast concrete girders and the ends of the CIP concrete box-girder webs to allow for splicing of the PT ducts. This end diaphragm also accommodated the end rotation of the precast concrete girders resulting from the deck concrete placement. The superstructure was post-tensioned once the deck and splice/closure pour concrete reached adequate strength.

This tied the precast and CIP concrete superstructure elements together to provide continuity, mimic the structural behavior of the existing bridge, and carry the live loads.

The bridge is composed of two frames. Frame A (abutment 1 to hinge 1) is approximately 318 ft long and Frame B (hinge 2 to abutment 2) is approximately 125 ft long. The 87-ft-long precast concrete drop-in span connects the two frames. Each tendon comprised either sixteen or eighteen 0.6-in.-diameter, Grade 270 low-relaxation strands. Frame A required three 18-strand tendons per girder, whereas Frame B required only two 16-strand tendons per girder. Jacking operations took place from the hinged ends of each frame. Post-tensioning from the hinge anchorages took advantage of friction losses, thus reducing the jacking forces in the precast concrete girder anchorage zones at the opposite ends.

The BNSF Railway has strict guidelines and restrictions concerning bridge construction within its right-of-way and over existing tracks. One key restriction prohibits falsework over existing railway tracks. As such, a portion of span 3 used precast, prestressed concrete drop-in girders.

The CIP concrete box girder cantilevered 19 ft 3 in. ahead and 11 ft 3 in. behind piers 2 and 3, respectively. The precast concrete girders were supported on CIP hinges (that is, beam ledges) and the ends of the girders were dapped to maintain a uniform structure depth. The webs of the precast concrete girders were flared at the ends to provide the necessary width for bearing and to provide the shear capacity needed as a result of the reduced depth at the dapped end. To provide visual continuity between CIP and precast concrete, the exterior webs of the CIP ledges were formed to match the end flares of the precast concrete girders' dapped ends.

Saving Time and Money

The existing bridge was widened about 120 ft, which equates to approximately 64,000 ft^2 of new bridge deck. Using precast concrete girders eliminated approximately 31,800 ft^2 of falsework, saving an estimated $954,000. In addition to the tangible monetary savings, another benefit was time savings. The worker hours required to erect and break down falsework could be directed toward other activities. There were also time savings associated with the concurrent construction of different bridge elements. Portions of the superstructure were no longer dependent on the completion of the falsework, thus allowing for the simultaneous construction of bridge substructure elements and the fabrication of precast concrete girders.

Conclusion

The widening of the Estrella Underpass at Grand Avenue bridge demonstrated that the usually obvious approach of "widen in-kind" is not necessarily the best approach.The hybrid concrete system used in the project provided a cost-effective solution to address common challenges encountered during urban freeway construction today. The prestressed and post-tensioned concrete superstructure provides durability, long service life, and low maintenance, essential properties necessary for the high traffic volumes—particularly truck traffic—this bridge will experience over its design life.

Construction of new Y-shaped columns at pier 3 with existing bridge pier 2 in the background. Photo: Haydon Building Corp.

John Lange is a senior engineer with Stanley Consultants in Phoenix, Ariz.

AESTHETICS COMMENTARY

by Frederick Gottemoeller

The first notable aspect of this project is the willingness of the design-build team to open their minds to all the options, not just the obvious ones, when addressing the myriad traffic maintenance and construction requirements of this complicated site. The second notable aspect is their willingness to consider good aesthetics as a legitimate criterion to be achieved at the same time as all of the functional requirements. Too often there is an unspoken assumption that achieving good aesthetics is an either/or proposition: we can solve all of the functional requirements or we can have good aesthetics, but we can't have both. This project proves that assumption to be untrue.

As one example of their open mind, let's take the team's decision to do all of the widening on one side, rather than symmetrically about the original centerline. The layout geometry is often presented to bridge engineers as if it were carved in stone, not to be adjusted no matter what opportunities it forecloses. By moving off the original centerline and widening all to one side, the team not only solved major traffic maintenance and construction problems, it allowed the original piers to be replicated, thereby ensuring that the new lanes would look integrated with the old as opposed to tacked-on additions.

As a second example of their open minds, let's take the team's decision to integrate precast concrete girders with cast-in-place concrete pier tables. Not only did this resolve serious construction issues and reduce cost, it also allowed the depth and shape of the original bridge to be emulated in the new construction. Recognizing that the precast concrete girders would inevitably look different from the cast-in-place concrete pier tables, the team even extended its concern for appearance to the details of the fascia girders at hinges and splices to ensure visual continuity across the whole bridge. This kind of attention to detail requires more care by the designers and builders, but its additional construction costs are not significant, while its aesthetic benefits are crucial. Urban underpasses like these are major components of our everyday lives. It is encouraging to see a design team make the effort to get one right aesthetically as well as functionally.

JOURNEY ACROSS THE SKYBRIDGE

by Danielle E. Chater and William R. Maples, CDM Smith,
and Patrick Carroll, Solid Waste Authority of Palm Beach County

Driving along the tree-lined lanes of Jog Road, one would not immediately recognize that a new state-of-the-art, energy-efficient, waste-to-energy facility is hard at work processing 3000 tons a day of post-recycled solid waste into 100 MW of electricity.

In order to give the public a full understanding of the benefits of the plant, Solid Waste Authority (SWA) of West Palm Beach, Fla., commissioned the Education Center, a LEED (Leadership in Energy and Environmental Design) platinum building. SWA then took their mission to educate the public one step further by incorporating a guided walking tour so that visitors have a complete experience. The guided tour makes use of the uniquely engineered Skybridge to provide access between the education center and facility's key buildings and control rooms.

The Skybridge

The Skybridge, a 534-ft-long elevated pedestrian walkway, rises 37 ft above grade and also acts as an educational tool. Its railings are adorned with information about various aspects of the facility, which can be viewed from all vantage points while on the journey across the Skybridge.

The superstructure primarily consists of precast concrete double-tee roof and

View from the Education Center roof garden looking south along the Skybridge with a focus on the supporting V-shaped piers. Photo: CDM Smith.

profile

SKYBRIDGE / PALM BEACH, FLORIDA

BRIDGE DESIGN ENGINEER: CDM Smith, Maitland, Fla., and Dura-Stress, Leesburg, Fla.

BRIDGE DESIGN ARCHITECT AND ARCHITECT OF RECORD: CDM Smith, Maitland, Fla.

PRIME CONTRACTOR: CDM Constructors Inc., Maitland, Fla.

PRECASTER: Dura-Stress, Leesburg, Fla.—a PCI-certified producer

CONSTRUCTION COST: $1.84 million

pretensioned members simply supported on V-shaped precast concrete columns. The main design reconciles several functional and aesthetic criteria, such as the plant's operational requirements and space limitations, while achieving the design concept of allowing the visitor to recognize that they are moving from the David-sized education center to the Goliath-sized power block. The openness of the V-shaped piers opening upwards towards the sky, and the height of the walking platform, were critical design factors in achieving this sensation.

The main design reconciles several functional and aesthetic criteria.

Multiple platforms provide intermediate viewing areas for groups to stop and observe their surroundings. At the platform areas, the wider deck was accomplished by using precast concrete solid slabs cantilevered across precast concrete beams that span between the piers. The viewing platform at the midpoint of the Skybridge doubles as an additional means of egress with precast concrete stairs leading from the platform to grade level.

The roof design uses two precast concrete double tees that slope from east to west to provide protection from driving rain and intense south Florida sun. The two double tees are connected with welded shear ties spaced at 6 ft on center. The high side of the roof on the east opens up to an unobstructed, panoramic view of the main elevations of the facility as well as the green landscaping and solar panels used throughout.

A precast concrete superstructure was selected to provide maximum durability with minimum maintenance. This system also was able to fit the tight assembly window during construction by being fully cast off-site and quickly installed on-site. During the design process, the designer worked closely with the precast, prestressed concrete supplier to take the Skybridge from the conceptual stage to the execution stage while maintaining the architects' vision.

Due to tight footprint restrictions associated with the adjacent buildings, the Skybridge foundations were designed as a cast-in-place (CIP) concrete pile cap on CIP piles. The design of the V-shaped Skybridge piers required significant moment-resisting connections at the pile caps. The piles were designed for tension with threaded tension bars and anchor plates. The pile cap–to–pier connection required close coordination with the precast, prestressed concrete supplier to accommodate the number, location, and development of the tension dowels that were grouted into splice sleeves after piers were erected. Temporary bracing remained in place until the grout reached design strength.

Execution Challenges

Many obstacles were overcome during the construction and installation of the elements making up the Skybridge.

The first obstacles were space and time constraints. Due to the fact that the Skybridge is nestled between the power block and adjacent buildings, construction sequencing and associated logistics had to be carefully planned. Planning had to consider a very short

The V-shaped piers supporting the deck and roof open up to the sky while meeting height requirements and site limitations. Photo: CDM Smith.

Precast concrete stairs shown during construction will provide egress at the viewing platform. Photo: Dura-Stress.

SOLID WASTE AUTHORITY, OWNER

BRIDGE DESCRIPTION: 534-ft-long, multiple-span elevated pedestrian double-tee walkway and roof with precast concrete solid slab viewing platforms

STRUCTURAL COMPONENTS: Ten V-shaped custom precast concrete piers supported on cast-in-place concrete pile caps bearing on cast-in-place piles. The piers support seven 8 ft by 32 in. precast concrete double-tee deck members for the bridge and 8 in. precast concrete flat slabs for the observation and staging decks. The roof structure consists of eighteen 8 ft by 24 in. precast concrete double tees (two double tees per span).

AWARDS: 2017 Florida Institute of Consulting Engineers: Engineering Excellence Award: Grand Award; 2016 American Society of Engineers: Project of the Year Award; 2016 Design-Build Institute of America Florida Region: Florida Design-Build Award, Industrial/Process/Research Facilities: Honor Award; 2016 *POWER* magazine: Top Plant Award; 2016 U.S. Green Building Council: Leadership in Energy and Environmental Design (LEED) Platinum Certification (Education Center); 2015 *American City and County* magazine: Crown Communities Award for Sustainability; and 2015 PCI Design Award: Best Non-Highway Bridge

Base of precast concrete V-shaped pier showing splice sleeves with ports for grouting. Photo: Dura-Stress.

period of time in which the crane could be used for superstructure installation. This aggressive installation occurred approximately six months after piling placement.

The second obstacle was coordination of the viewing platform and the windows at the power block. The windows needed to be located along the limited 36 ft span of the viewing platform while providing a clear, uninterrupted view to the interior of the building, at a height suitable for all spectators.

The third obstacle arose during the construction phase, when the connections at either end of the Skybridge had to be retrofitted due to variations in finished floor levels. Minor modifications to the waste-to-energy facility resulted in elevation differences between the staging platform and the power block elevator. The staging platform had to be designed to be supported on the Skybridge foundations while accounting for the high movement of the Skybridge relative to the power-block structure, thus creating a wide pedestrian expansion joint. The 2-in.-wide expansion joint with a cover was designed to account for the relative displacement between the Skybridge and the power-block elevator shaft.

Notched double tees are supported by haunches integral to the cross beams of the V-shaped piers. Photo: Dura-Stress.

Current Status

Solid Waste Authority's Palm Beach Renewable Energy Facility has many unique characteristics, with one of its most defining features being the precast concrete Skybridge. It has received numerous awards and accolades for its unique design and innovative structure.

The Skybridge not only performs its most basic function of providing a means of access between the education center and the power block, but also creates a journey of education through time and space across the facility.

Perhaps the most endearing feature of the Skybridge is its ability to bridge the gap between the theory of a sustainable world and the actual reality of living in one.

At the education-center end of the Skybridge, the platform from the roof garden to the bridge was built slightly higher in elevation than anticipated, leading to necessary adjustments in the construction of the Skybridge. The first span of the Skybridge was designed to cantilever over the first V-shaped pier to minimize structural loads on the education center's architectural features. The design of the specialty double tee accommodated the increased dead load caused by placing a concrete topping over the walkway to reconcile the difference in elevations. The concrete topping was installed as a built-up slope over the run of the first section between columns. All other spans of the bridge were simply supported with notched double tees bearing on haunches that were integral to the cross beams of the one-piece V-shaped piers. Expansion joints were constructed over the support beams and reflected through the concrete topping on the walking deck. On the roof deck, the joints were accommodated with flexible covers over the roofing material.

Danielle E. Chater is an architect and William R. Maples is a senior structural engineer with CDM Smith in Maitland, Fla. Patrick Carroll is director of capital programs with Solid Waste Authority of Palm Beach County in West Palm Beach, Fla.

ANTLERS BRIDGE

by Jason Lynch, California Department of Transportation

In Northern California, Interstate 5 follows a historical route through the Sacramento River Canyon, and the new Antlers Bridge is one of its significant structures. The 1942-ft-long bridge crosses Shasta Lake, near the community of Lakehead, on a new alignment to replace an aging truss. For the California Department of Transportation (Caltrans), the $131 million project improves a critical link for the movement of people and goods in the West. For the general contractor, it presented a host of challenges, requiring innovation and flexibility.

Replacement Needed

The structure replaces a narrow steel deck truss built during the construction of Shasta Dam in 1941. Its active structural-steel fatigue cracks and a deteriorating deck made the existing bridge an annual drain on the state's maintenance resources. The approach highway lacked shoulders and had a steep, tightly curved alignment that could drive like a luge run.

New Design

Seeking to improve safety and reduce long-term costs, the state realigned the roadway and opted for the durability and ease of maintenance of a cast-in-place, prestressed concrete box-girder bridge. The height of the bridge and the challenging site access discouraged California's typical falsework construction, driving the project to the balanced-cantilever, segmental method.

Vehicles on the new bridge and the final days of the old truss. All Photos: California Department of Transportation.

Designers located the piers to miss the greatest depth of the lake and a recreational hot spot fronting the Antlers public boat ramp. The result was a bridge with five continuous spans and a 591-ft-long main span. Symmetry in the layout and the box-girder dimensions helped to economize on equipment and formwork costs. The design followed the *AASHTO LRFD Bridge Design Specifications*, supplemented by project-specific criteria. For bridge trivia buffs, the effort holds the inconsequential distinction of being the last California bridge designed in metric units and among the first using the load-and-resistance-factor design method.

Design Challenges

Caltrans's *Seismic Design Criteria* requires ductility and resilience of all California bridges, particularly for operationally important structures. With a two-lane detour more than 100 miles long, this lifeline structure needs to perform. But performance would come

profile

ANTLERS BRIDGE / LAKEHEAD, CALIFORNIA

BRIDGE DESIGN ENGINEER: California Department of Transportation (Caltrans), Sacramento, Calif.

PRIME CONTRACTOR: Tutor-Saliba Corp., Sylmar, Calif.

POST-TENSIONING CONTRACTOR AND FORM TRAVELERS: Schwager-Davis Inc., San Jose, Calif.

CONTRACTOR'S ENGINEER: Finley Engineering Group, Tallahassee, Fla.

at a steep price, the amount of extra pier-table reinforcement needed.

One sees a panoramic view of Shasta Lake from those pier tables. It is the largest reservoir in California, filling the Sacramento and two other river canyons above Shasta Dam. The dam's original function was salinity control for the agricultural delta off San Francisco Bay, but its modern roles include water supply and flood protection, competing objectives that cause the lake's surface to fluctuate vertically as much as 50 ft in a normal year.

Unfortunately, after five years of a statewide drought, normal years have been quite the anomaly. At the construction site, 20 miles from the dam, the Sacramento River changed from deep lake to trickling stream—and back again—with only 120 ft between its extremes.

Anticipating the challenge, the designers sought a foundation type that was both constructible and visually appealing in either high or low water conditions. Potential high water conditions precluded traditional cofferdams, and low water would make an eyesore and boating hazard out of any suspended pile cap. The design team turned to 12-ft-diameter drilled shafts extending between 95 and 140 ft to the superstructure. The shafts were a versatile solution, but constructing them required much time and money.

Massive columns are monolithic with the heavy pier cap.

Drought left the access trestle high and dry.

In November 2009, the contractor cleared staging areas and drove trestle piles in the dry conditions of a nearly empty Shasta Lake. It was an enthusiastic start, but heavy rains flooded the site, overtopped the temporary works, and pushed activity to higher elevations. A combination of barges and even loftier trestles—up to 95 ft tall—provided access to subsequent work.

Shaft construction began with a sacrificial 14-ft-diameter construction casing vibrated 25 to 60 ft into the canyon's sloping, degraded rock. Ribbed with 6-in. angles above ground, the 1-in.-thick casing would ultimately serve as a 90-ft-deep cofferdam for the dry placement of column concrete. In the drilling phase, its primary functions were to control turbidity, to increase the precision of the shaft position, and—when the lake went dry—to provide hydraulic head over the drilling tools.

After excavating within the construction casing, the contractor used reverse circulation drilling to advance the shaft up to 70 ft into more competent rock. To reduce the risk of caving in the open hole, several operations were conducted in quick succession after the drill string was removed. A sonic caliper assessed

CALIFORNIA DEPARTMENT OF TRANSPORTATION (CALTRANS), OWNER

OTHER SUPPLIERS: Harris Salinas Rebar Inc., Livermore, Calif.; Shaft Drillers International, Mt. Morris, Pa.; Spec Form Liner, Santa Ana, Calif.; and Stimpel-Wiebelhaus Associates, Redding, Calif.

BRIDGE DESCRIPTION: Five-span continuous, post-tensioned, cast-in-place, segmental concrete box-girder bridge, 104 ft wide and 1942 ft long, with a 591 ft main span, all founded on 12-ft-diameter drilled shafts

STRUCTURAL COMPONENTS: 212 box-girder segments 13 to 15 ft long, 12 to 30 ft deep; 63 by 104 by 36 ft deep pier tables supported by 12-ft-diameter drilled shafts; and transversely post-tensioned, cast-in-place concrete deck

BRIDGE CONSTRUCTION COST: At least $131 million

Construction casings and access trestles were built when the lake was full but are exposed when the lake is low.

Falsework was used near the bridge abutments.

the hole for plumbness, and a miniature drilled shaft inspection device verified the bottom cleanliness. Prefabricated, 80-ft-long reinforcing cages were then lowered into the shafts, followed by tremied concrete with a 6-ksi strength requirement. Caltrans tested the hardened concrete for homogeneity using gamma-gamma density logging. Of the 12 shafts, six contained minor anomalies that were repaired by grouting.

On to the Pier Tables

As the foundations were completed, and each shaft extended upward as a column, attention turned to the 63 by 104 by 36-ft-deep pier tables. At the main piers just one of these massive elements would consume 4350 yd^3 of concrete from an on-site batch plant. Architectural details required complicated, curving formwork. Brackets embedded in the bridge columns supported an impressive falsework system above the water line. Seismic design required nearly one million pounds of reinforcing steel in each of the main pier tables. The congestion and scale prompted the contractor to use self-consolidating concrete, placing three separate lifts over the course of several weeks. Individual concrete placements lasted up to 20 hours. Mass concrete specifications required cooling pipes and thermal monitoring during and after concrete placement.

Segments

Once a pier table was finished, the contractor erected four 1200-kip form travelers to support the cast-in-place concrete segmental construction. The 212 superstructure segments were 13 to 15 ft long and weighed up to 400 kip. After an initial learning curve, construction settled into a routine of casting four segments per week. Each segment was prestressed 18 to 24 hours after it was cast, once an on-site lab broke test cylinders at a minimum of 3.6 ksi.

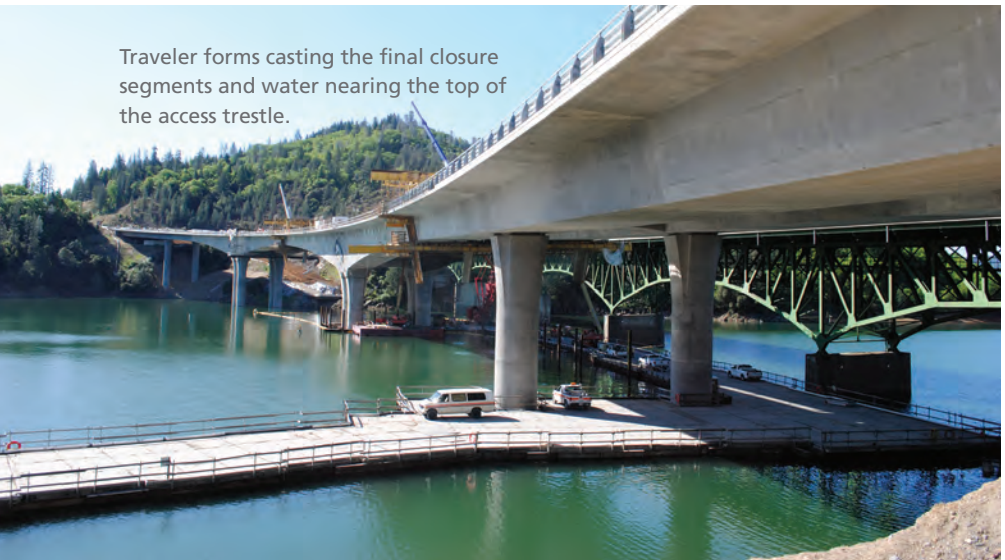
The superstructure cross section is a double-box girder, each box being 50 ft wide and 12 to 30 ft deep and connected by a 4 ft longitudinal closure strip. The overall width is 104 ft on a 4% cross slope, carrying five lanes of traffic between open steel barriers. The asymmetric traffic layout—owing to a southbound truck climbing lane up the 6% grade—drove the decision to connect the otherwise symmetrical boxes.

Longitudinal prestressing tendons—twenty-five 0.6-in.-diameter strands in each box-girder web—keep the superstructure in compression under live load. Some segments were vertically prestressed with high-strength bars to manage principal stresses.

Durability for the Future

After decades of maintenance on the fatigued and ailing truss, durability and long life became touchstones of the Antlers Bridge project. The no-tension requirement is one of several strategies to that end. Transverse post-tensioning, epoxy-coated reinforcement, 2.5-in. concrete cover, and a polyester concrete overlay also contribute to the durability of the new deck.

The bridge went into service in late 2016, and demolition of the old truss is nearly complete. After seven years of construction, boaters can look forward to open water while motorists will enjoy an open road. Caltrans expects the new Antlers Bridge to last in excess of 100 years.



Traveler forms casting the final closure segments and water nearing the top of the access trestle.

Jason Lynch is a senior bridge engineer with the California Department of Transportation in Sacramento.

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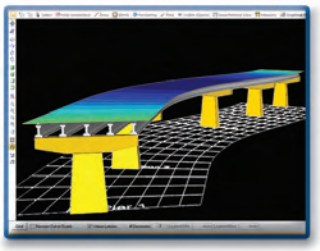

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UHPC is a Game-Changing Material for Bridge Producers

by J. P. Binard, Precast Systems Engineering

Editor's Note
A longer version of this article was published in the March-April 2017 issue of the PCI Journal.

Five members of the TechnoQuest team with Dr.Voo (in white shirt) on the UTC Perak Footbridge. Not pictured: Maher Tadros. Photo: Precast/Prestressed Concrete Institute.

Last year, ultra-high-performance concrete (UHPC) generated considerable buzz in the concrete bridge industry. In March, during the Precast/Prestressed Concrete Institute's (PCI's) Convention and National Bridge Conference in Nashville, Tenn., Dr. Yen Lei Voo gave a presentation on the remarkable uses of nonproprietary UHPC solutions by his company, DURA® Technology, to the PCI Committee on Bridges, which includes bridge design engineers, owners, and producers. Then in July, the First Interactive International Symposium on Ultra High Performance Concrete was held in Des Moines, Iowa. At that symposium there were site visits, presentations, and interactive panel sessions moderated by experts. The Summer 2016 issue of *ASPIRE*™ included an article titled "Taking Ultra-High-Performance Concrete to New Heights."[1] In September, fib task group 6.5 held a meeting in Malaysia and PCI conducted a TechnoQuest to visit DURA's facility located in Ipoh, Malaysia, at the same time. As shown in the photograph above, the PCI group included (from left to right) Dr. John Lawler (WJE), Mason Lampton (Standard Concrete Products), J.P. Binard (formerly with Bayshore Concrete Products), our host Dr. Voo, Jim Fabinski (ENCON Colorado), and William Nickas (PCI's managing director of transportation systems). Dr. Maher Tadros (e.construct USA LLC) also attended but was not in the photograph. Finally, in November Dr. Voo gave a presentation on his material and accomplishments during the opening session of the American Segmental Bridge Institute (ASBI) Convention in Long Beach, Calif.

The PCI TechnoQuest group was inspired by Dr. Voo's presentation to embark on this journey to Malaysia because to date, UHPC has not been considered a viable, consistent option for precast concrete components in the United States. DURA, however, is producing large components fabricated from UHPC that are incorporated into a variety of bridges throughout Malaysia. These bridges include the longest UHPC single span in the world, as well as the longest composite bridge fabricated with UHPC in the world, which is currently under construction. The company utilizes a facility solely focused on UHPC that directly competes with conventional structural solutions.

The Game-Changing Material

UHPC is not a new material. Projects and publications throughout the world have highlighted this material and its various applications in bridges, buildings, and other sectors for about 20 years.[2] With nonproprietary versions of this class of material becoming more commonplace,

Batu 6 segmental box-girder bridge with 100 m (328 ft) span. Photo: DURA Technology.

Post-tensioned U-beam segments produced by DURA Technology. Photo: Precast/Prestressed Concrete Institute.

there is a great opportunity to advance the industry by adding this material to our repertoire.[3] A new market share may be viable when UHPC components are applied as an overall bridge solution.

A standard prestressed concrete bridge girder merely cast with UHPC instead of high-performance concrete is not cost effective. However, a modified section utilizing 40% to 50% less material with less reinforcement and extending the span of the structure with the same depth as an equivalent steel section becomes an attractive alternative.

With less material, superstructure weights are less, thereby reducing foundation costs. Onsite crane and lifting requirements become similar to those for steel beams. Perhaps other UHPC elements can be combined to reduce the overall structure weight further, resulting in more efficient use of the material. Automating precast, prestressed concrete manufacturing to new levels with less, or perhaps no, manual labor may be possible.

Several challenges and limitations pertaining to precast, prestressed concrete components are diminished or eliminated by implementing UHPC.

Clear Cover and Crack Control

UHPC minimum clear cover can be as little as ¾ in. Steel fibers within the matrix of the UHPC take the place of conventional crack-control reinforcement.

Camber, Creep, and Shrinkage

UHPC components, after a secondary stage of curing at 194°F for 48 hours, implemented within 14 days after detensioning or demolding, exhibit a really low creep and shrinkage rate that may be considered zero for computations.[1] Therefore, the camber measured in a fabricator's yard will remain constant, which leads to a predictability or a tolerance similar to that of steel products. Post-tensioned systems will incur significantly fewer losses due to the essentially nonexistent creep and shrinkage of prefabricated UHPC components.

Development and Bond

The bond capability of UHPC is chemical. Therefore, at ultimate strength the fibers pull out rather than fracture, leading to stress relief in lieu of damage. Development of strand and nonprestressed reinforcement as well as lap-splice lengths are also greatly reduced when compared to conventional concrete.[4]

End Regions

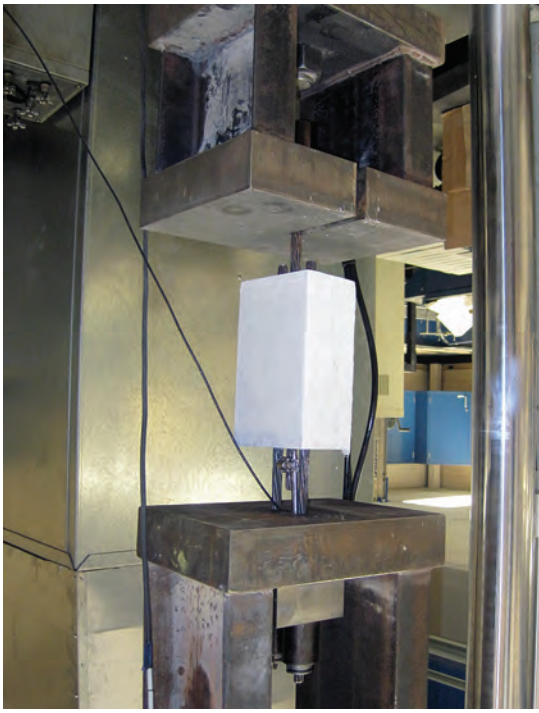
UHPC simplifies end regions of beams by greatly reducing or eliminating shear reinforcement, splitting reinforcement, and confinement reinforcement,[5] and also provides a shorter development length for longitudinal reinforcement.

Detailing and Reinforcement Placement

UHPC may not require nonprestressed reinforcement apart from potential connections, if applicable, such as for a composite deck, closures for continuity, and the like. Therefore, labor is greatly reduced in the plant. This, along with detailing alterations such as potentially closer spacing of strands and clear cover no longer governed by confinement reinforcement, allows greater eccentricity of the prestressing force relative to the centroid, thereby leading to more efficient use of the material, as illustrated by the comparison of details on the following page.

Compression-Controlled Release Strength and Temporary Tensile Stress Control

A UHPC element is likely to have a reduced cross section because of the significantly greater strength and toughness of the material. Passive reinforcement is not required, so concrete cover is less of a limiting factor, also allowing a smaller cross section. Hence, utilizing the higher early and long-term compressive and tensile strengths allows UHPC elements to be designed without debonding or draping of strands, thus resulting in more efficient production.



Lap-splice test of untensioned strands in ultra-high-performance concrete. Photo: Federal Highway Administration.

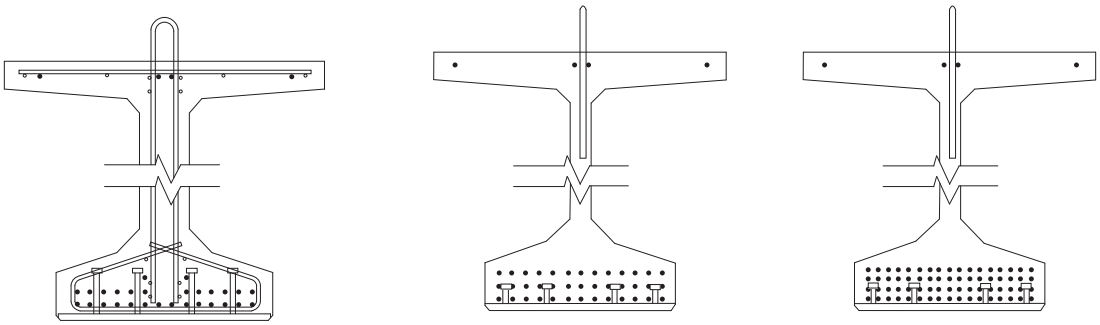
Implementing UHPC

There are essentially no adverse effects to the general contractor if UHPC is selected as the material for a component instead of another material. Fabrication activities, however, require greater attention in casting, material selection and handling, cleaning of forms and surfaces, form geometry, and curing. One unique aspect of DURA's approach to casting is that its molds are sized to accommodate a single batch from its mixer.[1] This approach ensures consistency and uniformity of the mixture within an element and entirely removes the risk of a cold joint or anomaly during a multiple-batch casting. The components are match-cast and all products cast in this manner are connected via thin shear keys that have been validated through testing.[6] The segments are then post-tensioned together in the field to achieve the span length.

The material is expensive. One clever idea observed at DURA is how it utilizes its surplus concrete in making small ¾-in.-thick, stay-in-place forms for cast-in-place concrete deck placement. Top corners of beams are notched to provide a simple seat for these panels so they can be set easily by the contractor and not affect the overall deck thickness.

Conclusions

Opportunities to redefine an industry or define new markets do not arrive every



Comparison of details for standard bulb tee and ultra-high-performance concrete alternatives. Drawing: Precast Systems Engineering.

DURA Technology's stay-in-place precast concrete deck form panel. Photo: Precast/Prestressed Concrete Institute.

day. Refinement of prestressed, precast concrete has occurred incrementally over the past decades. However, UHPC is a complete game-changing material, capable of spawning a new renaissance for the industry while meeting infrastructure demands now and in the future.

Therefore, when looking into the future and how UHPC will benefit bridges, producers should not merely replace today's concrete with UHPC. When this industry was developed, research and testing in universities was not as common as it is today. There was a boldness in the founders of the industry along with an incredible vison to understand the potential of this new type of business. Precast, prestressed concrete bridge solutions are well positioned to embrace this technology and advance these and other possibilities to the next level.

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J. P. Binard, the former chief engineer of Bayshore Concrete Products, which he represented while attending the TechnoQuest, is a consultant with Precast Systems Engineering LLC.

EDITOR'S NOTE

To participate in this exciting new opportunity, please contact the author at binard.jp@gmail.com or attend the next meeting of the UHPC Subcommittee to the PCI Committee on Bridges.

Salt Creek Half-Viaduct Bridges Rehabilitation Using Full-Depth Precast Concrete Deck Panels

by Dr. Keith Kaufman, Knife River Corporation

Heavy haul trucks that travel between Portland, Ore., and Weed, Calif., have few route options. Trucks can stay on Interstate 5 (I-5) and deal with multiple passes between Eugene, Ore., and Medford, Ore., before climbing the Siskiyou Summit that is south of Ashland, Ore., and continuing on to Weed. Another popular freight route uses Oregon Route 58, which heads east out of Eugene and over the Cascade mountains to Highway 97 near Chemult, Ore. That route then follows a relatively flatter grade to Weed by avoiding the Siskiyou Summit.

A 1933 construction photo at the Salt Creek Tunnel's west entrance with a half-viaduct bridge visible. Photo: Oregon State Archives.

Oregon Route 58 is a two-lane highway that leaves the Willamette Valley at an elevation of 500 ft and climbs the Cascade Mountains, reaching a peak elevation of 5100 ft at Willamette Pass. An integral part of this route is the Salt Creek Tunnel, which lies west of the summit at an elevation of 3850 ft. Four half-viaduct bridges are located outside the tunnel: one to the west and three to the east. At each of these locations, the westbound lanes are on grade while the eastbound lanes are supported across multiple grade openings using reinforced concrete deck-girder bridges or half viaducts

The geometry of the tunnel grade was modified by lowering the roadway to improve vertical clearance. Other improvements include applying shotcrete to the walls, and upgrading utilities. The four viaducts also required reconstruction to alleviate years of deterioration and improve the safety of the system. The Oregon Department of Transportation (ODOT) completed a redesign in 2012.

Design

Due to historical requirements, the new bridges had to simulate the T-beam construction of the existing bridges. Therefore, the engineer of record (EOR) detailed a spread 42-in.-deep precast, prestressed concrete box-beam system carrying a 10-in.-thick cast-in-place (CIP) composite concrete deck that would receive a 4-in.-thick asphalt overlay. The thick deck and overlay help resist potential debris slides and avalanche impact. Furthermore, the EOR limited the live load deflection at the longitudinal joint between the eastbound viaduct and the westbound grade so that the asphalt overlay could be continuous over the eastbound and westbound lanes.

The individual span lengths are 50 ft on all viaducts with two to five spans in each bridge. The four bridges include longitudinal grades of 4% to 5%. Three of the bridges are on a horizontal curve with a constant cross slope.

The EOR's design included a precast concrete-friendly design for the box beams. All pile caps were parallel, being normal to the chord of the arc. Therefore, all precast concrete box beams were the same casting length. A chamfer or fillet detail was included at the ends to incorporate the proper offset to the curve. The fourth bridge is on a tangent. However, it included a reverse super-elevation.

ODOT specified its three-tube curb mount rail. The exterior of the curb included a formliner for aesthetics. These details are visible from the Salt Creek Trail below the roadway.

A heavy haul truck uses the Salt Creek Tunnel. The truck transports a girder through the east portal to another project. Photo: Knife River Corporation.

Value Engineering and Special Considerations

The construction site and schedule were very restricted. The weather limited construction to the late spring, summer, and early fall, depending on snow. Oregon Route 58 was closed during weekday nights to allow for construction. Daily closures were limited to 15 minutes to allow alternating single-lane traffic movements.

After the bid, the contractor contacted the manufacturer of the precast concrete box beams, Knife River, and asked whether a full-depth precast concrete deck panel could replace the CIP deck. A post-tensioning supplier, DSI, was contacted and details were provided for a system used in Utah that was pretensioned transversely and post-tensioned longitudinally. This system was submitted and approved. For the three bridges on a horizontal curve, pie-shaped deck panels were detailed. The panel width was set to match the rail-post spacing of 9 ft so that all panels were the same in each bridge.

Precast concrete deck panel with joint and pocket details visible. Photo: Knife River Corporation.

This photo shows westbound traffic exiting the west tunnel portal. A completed half viaduct carries east bound traffic into the tunnel. Photo: ODOT Region 2.

Typical elevation of completed half-viaduct bridge. Photo: ODOT Region 2.

Some special considerations are discussed in the following sections.

Substructure

The CIP caps at all piers are supported on piles. The top of the pile cap is parallel to the deck cross slope. Between the eastbound and westbound lanes, precast concrete gravity blocks were stacked. The tops of the gravity blocks received a keyed coping slab to complete the westbound lane.

Box Beams

The box beams were erected parallel to the cross slope. An integral diaphragm was cast over each pier to lock the superstructure to the substructure. The box beams have a straight strand pattern with a few top strands to minimize camber and stresses at the ends.

Precast Concrete Deck Panels

The 10-in.-thick precast, prestressed concrete deck panels were pie shaped with an exterior dimension of 9 ft and an interior dimension less than 9 ft to match the roadway geometry. The transverse shear key between panels included pockets at the post-tensioning duct for splicing. Reinforcement was extended longitudinally to complete the exterior curb and rail, and also to complete the interior closure. At each abutment, a CIP concrete panel was cast to complete the deck.

The transverse prestressing of the deck panels included two rows of ten 1/2-in.-diameter, Grade 270 pretensioned strands, a row at the top and bottom. Longitudinally, post-tensioning tendons were spaced at 2 ft 6 in. Each tendon included four 0.6-in.-diameter, Grade 270 post-tensioning strands. The concrete compressive stress in the deck from prestressing after losses was approximately 500 psi transversely and longitudinally.

Composite Action

Due to the arc geometry of the panels and linear alignment of the box beams, a unique system was incorporated to complete the composite section. A similar system was used in the Bronco Bridge in Denver, Colo. (see the Summer 2013 issue of *ASPIRE*™). Four-legged No. 5 stirrups were extended from the top of the box beam into the buildup. Then, No. 5 ties were placed in the blockout. Longitudinal bars were added to complete the reinforcement of the connection.

Construction Sequence

The construction sequence was:

1. Precast concrete box beams were erected.
2. Diaphragms were cast to connect the ends of the box beams to each other and to the pile caps.
3. The precast concrete deck panels were erected on the box beams.
4. The composite reinforcement (No. 5 ties) was added in each blockout and secured to the longitudinal reinforcement. Leveling screws and rigid-foam strips were used to establish the build-up geometry and provide a form for the CIP composite concrete.
5. Longitudinal post-tensioning ducts were spliced at the transverse joints and then the transverse shear keys were cast and cured. Longitudinal post-tensioning was applied and ducts were grouted. The panels were post-tensioned for the length of the structure.
6. The build-up and shear pockets received the composite concrete to complete the structural system.
7. To complete the superstructure, closure panels, traffic barrier, and a longitudinal edge casting between the precast concrete deck panels and the CIP grade slab over the eastbound lane were installed, followed by an asphalt overlay and a saw-cut joint.

Summary

The project had many challenges. However, the use of precast concrete components allowed the project to be completed rapidly in the difficult environment.

Dr. Keith Kaufman is the chief engineer with Knife River Corporation in Harrisburg, Ore.

High-Strength Steel in Bridge Applications

by Dr. Maher K. Tadros, e.construct USA.LLC

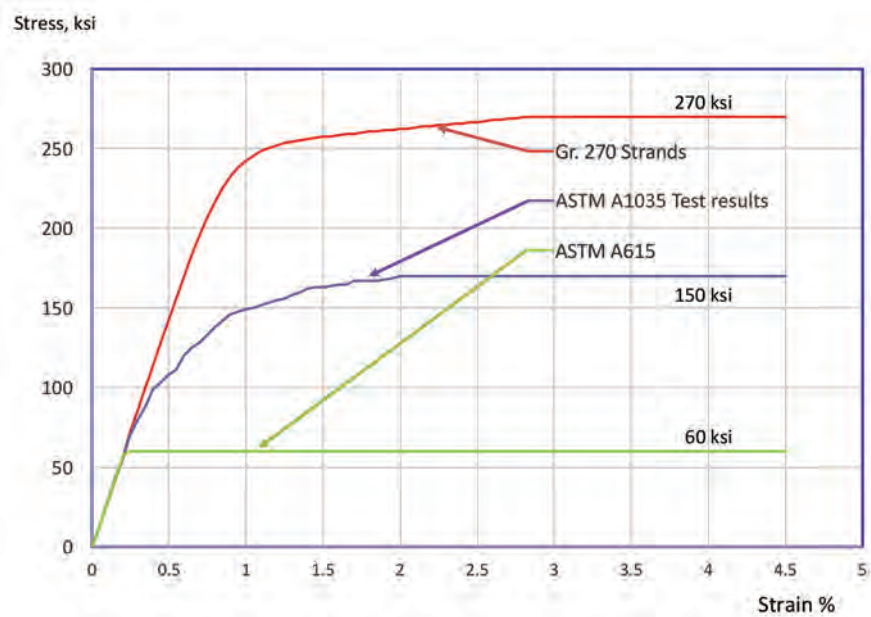

Figure 1. Comparison of stress-strain relationship for various steel types including ASTM A1035-CS alloy series with 100 ksi yield strength. All Photos and Figures: e.construct USA.LLC.

The most common type of reinforcing bars used for passive reinforcement of concrete in the United States is Grade 60 ksi steel conforming to ASTM A615/A615M, *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*. Grade 270 ksi, seven-wire prestressing strand, conforming to ASTM A416/A416M, *Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete*, has been used for prestressing, both pretensioning and post-tensioning. The strand grade has not changed for more than 40 years.

In the meantime, both concrete strengths and reinforcing bar strengths have experienced significant increases in the past 20 years. Concrete strength has nearly doubled from about 5 ksi to about 10 ksi in common practice. Concrete with strengths even as high as 22 ksi, which is known as ultra-high-performance concrete (UHPC), has been used in several projects.

A steel grade with a yield strength of 100 ksi was recently introduced into the ASTM A615 standard. Both the American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)* and the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* have recognized the higher strength reinforcing bars and have allowed use of 100 ksi steel in some applications and 75 to 80 ksi in others. Over the past 15 years, a new type of steel, which combines high strength with corrosion resistance and conforms to ASTM A1035/A1035M, *Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement*, has been recognized in North American building codes. The introduction of this corrosion-resistant high-strength steel into the AASHTO LRFD specifications was based on recommendations from National Cooperative Highway Research Program (NCHRP) Project 12-77 by Shahrooz et al.[1] Figure 1 shows the stress-strain relationship for the various steel types.

It seems logical to try to combine high-strength concrete with high-strength steel to optimize structural members and systems; however, limitations exist. This article focuses on introducing corrosion-resistant high-strength steel conforming to ASTM A1035/A1035M. Examples of successful applications are also given.

What Is ASTM A1035 Steel?

The proprietary high-strength steel meeting ASTM A1035 specifications is manufactured in the United States and other countries under license from MMFX Technologies, Irvine, Calif. ASTM A1035 has three basic series: 2000, 4000, and 9000, representing a chromium content of 2, 4, and 9%, respectively. The highest chromium content is the 9000 series, also known as ASTM A1035-CS alloy. It is the most expensive and is used for the highest corrosion-resistance applications, for example bridge decks. The 4000 series is known as ASTM A1035-CM alloy. The 2000 series, also known as ASTM A1035-CL alloy, is the least expensive and can be used where low-corrosion resistance is acceptable, for example columns (generally where they are under axial loads and flexural strains remain small) and interiors of buildings.

Strength and Ductility

ASTM A1035 also specifies other chemical composition requirements, most notably carbon content. The 2000, 4000, and 9000 series have maximum carbon contents of 0.30%, 0.20% and 0.15%, respectively. The chemical composition allows all three series to have a yield strength of at least 100 ksi and a tensile strength of at least 150 ksi. There are actually six series of ASTM A1035

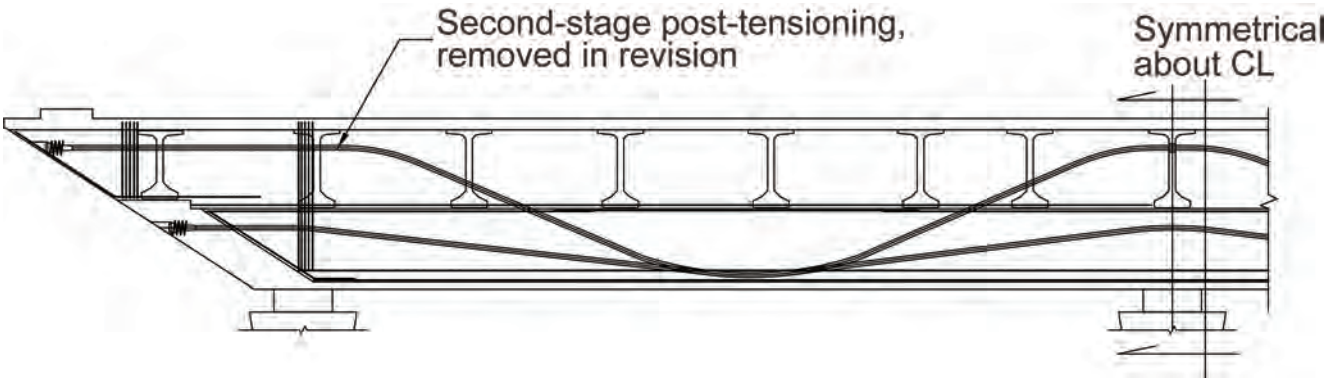

Figure 2. Partial view of pier crosshead showing two-stage post-tensioning.

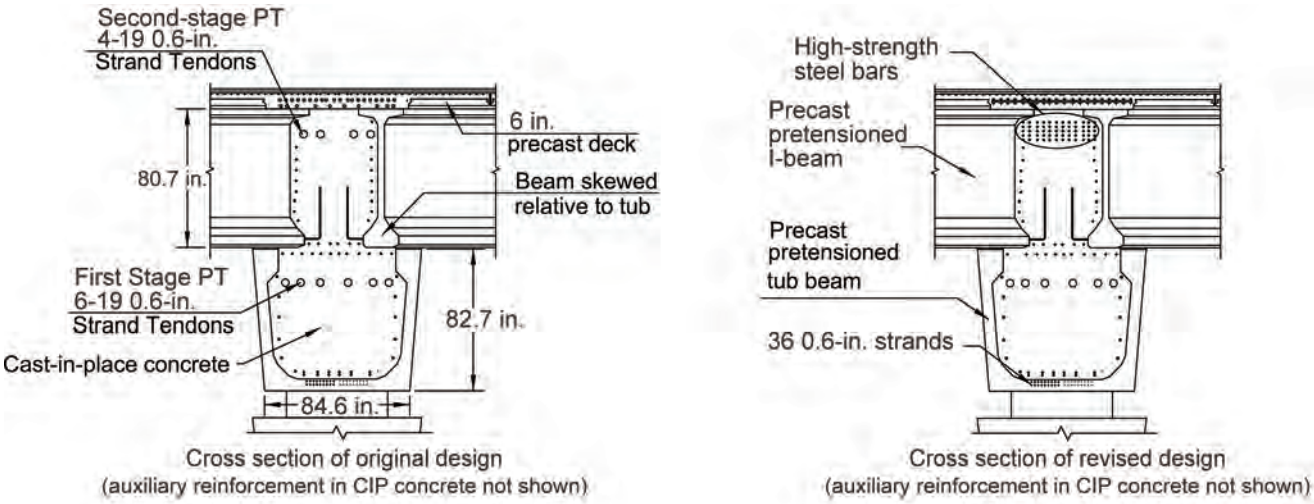

Figure 3. Typical cross sections of pier crosshead with revisions to replace post-tensioning with ASTM A1035-CS alloy steel.

steel: 2100, 2120, 4100, 4120, 9100, and 9120, ranked from the least yield strength and corrosion resistance to the highest strength and corrosion resistance.

ASTM A1035-CS alloy steel has excellent ductility with a minimum ASTM required ultimate elongation of 7% for bar sizes No. 3 through No. 11 and 6% for No. 14 and No. 18. These are the same limits specified in ASTM A615 for Grade 75/80 steel, but are slightly less than the limits for Grade 60 steel.

Corrosion Resistance

Reinforcing bar corrosion begins when the chloride concentration at the steel surface reaches the critical chloride threshold (CT) of the steel. The CT of ASTM A1035 Grade 9100 is four times that of ASTM A615 steel bar and twice that of ASTM A1035 Series 4100.[2-4]

The AASHTO Standard Specification MP 18M/MP 18[5] covers two types of steel that should be investigated by owners and their consultants for applications requiring uncoated corrosion-resistant bars: ASTM A1035 Series 9100 and stainless steel conforming to ASTM A955/A955M, *Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement*. The minimum chromium content in stainless steel is 12% and is 9.2% for ASTM A1035 Series 9100. Thus, stainless steel is more corrosion resistant. However, stainless steel is significantly more expensive and has a yield strength of only 75 ksi.

Structural Design Considerations

The biggest reduction in the amount of steel, when A1035 steel is used, is realized for flexural-tension reinforcement controlled by strength limit state. To take full advantage of high-strength steel, the compressive strength of the concrete should be high enough to drive the neutral axis towards the compression face of the section, achieving so-called tension-controlled behavior. This is not difficult to achieve in practical applications. Other limits to be aware of are

- minimum reinforcement to avoid sudden tension-initiated failure, and
- crack and deflection controls, which limit the amount of reduction of steel that can be realized.

A recent study[4] showed that when the bar size is reduced by one size and cover is reduced by 1/2 in., high-strength bar resulted in less cracking than black Grade 60 reinforcing bar. In cases where crack width at the concrete face is an important design criterion, designers should be aware that reducing the steel area alone could result in an increase in crack width. The designer should consider reducing the bar size, bar spacing, and concrete cover over reinforcement.

Members subjected to combined flexure and axial load could be optimized to by replacing Grade 60 with ASTM A1035 steel with a yield

Figure 4. ASTM A1035-CS alloy reinforcement cage being placed in a segment form for the Lesner Bridge in Virginia Beach, Va.

strength of 100 ksi. However, using conventional assumptions for flexural strength analysis, the maximum usable concrete strain at the strength limit state is 0.003 (see the seventh edition AASHTO LRFD specifications article 5.7.2.1 or the eighth edition AASHTO LRFD specifications article 5.6.2.1).[6] With the modulus of elasticity of steel assumed to be equal to 29,000 ksi, the maximum stress that can be achieved in compression reinforcement is 87 ksi. This is why ACI 318-14 limits the strength of steel in the compression zone to 80 ksi. The designer may be able to overcome this restriction by providing confinement (lateral) steel that increases the extreme fiber concrete strain to 0.0035, which incidentally is the ultimate strain used in some Canadian and European codes.

The maximum yield strength of steel that can be used when designing for shear is 80 ksi in ACI 318-14, but the seventh edition of the AASHTO LRFD specifications allows the use of 100 ksi in Seismic Zone 1. The reason for limiting the use of the higher strength to Seismic Zone 1 in AASHTO is that tests are only available for non-seismic applications.[1] However, the AASHTO LRFD specifications do allow use of 100 ksi in seismic applications with owner approval. The designer must be careful to make sure there is no diagonal tension cracking in prestressed concrete thin-web members at the service limit state because such cracking could create fatigue conditions (see article 5.8.5 of the seventh edition AASHTO LRFD specifications or article 5.9.2.3.3 of the eighth edition AASHTO LRFD specifications).

There are many other applications where corrosion-resistant Grade 100 steel can be used. They include bridge decks, retaining walls, piles and columns in salt water, foundations, columns and walls in high-rise buildings and bridges, auxiliary steel in segmental box-girder bridges, and continuously reinforced concrete pavements.

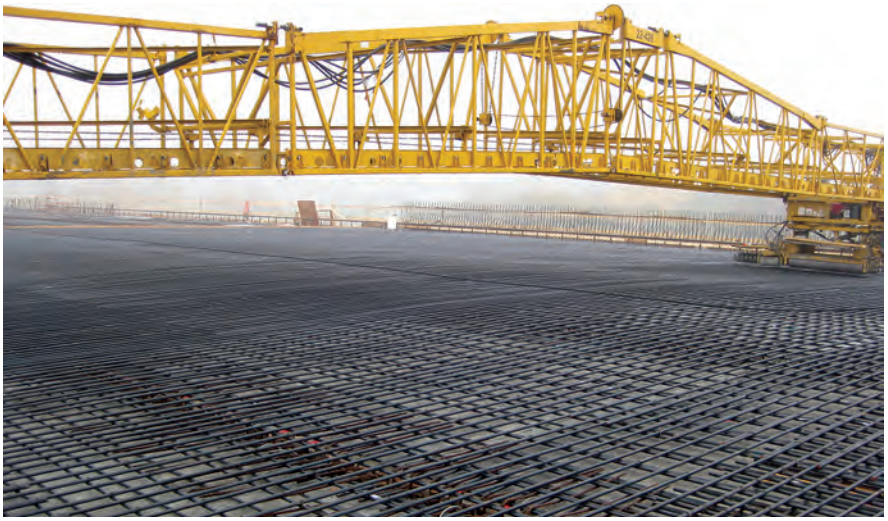

Figure 5. Deck for Circle Drive Bridge in Saskatoon, Canada, with conventional Grade 60 reinforcement replaced with ASTM A1035 CS Series 9100.

Cost of ASTM A1035 Reinforcing Steel

It is hard to give an accurate cost comparison based on increased strength alone without considering the benefit of corrosion resistance. Using high-strength steel has more benefits than just reducing steel quantities, such as reduced fabrication costs and steel congestion. As a general guide for initial estimates, one can assume that ASTM A1035 Series 9100 costs slightly less than $1.00 per pound, with lower grade materials costing less. ASTM A1035 Series 4100 costs about the same as epoxy-coated ASTM A615 steel.

Projects Using High-Strength Reinforcement

The following section are some recent applications of ASTM A1035 reinforcement in bridges.

The Abu Dhabi International Airport Departure Bridge

The Abu Dhabi International Airport Departure Bridge had a challenging pier crosshead. The bridge was curved in plan and had unusually heavy design loads and sharply skewed pier crossheads (caps) with very few column supports. Figure 2 shows the elevation of one of the crossheads. The nearly 16 ft superstructure depth had to be constructed in two stages.

Figure 3 shows a typical cross section before and after revisions were made to replace the second-stage post-tensioning with ASTM A1035-CS alloy steel. The revisions allowed for simpler, faster construction with reduced congestion. The first-stage post-tensioning ensured adequate precompression of the positive moment zone. The passive ASTM A1035-CS alloy reinforcement for negative moment was only placed where needed, rather than full length, and its installation did not require the presence of a specialty subcontractor. It also reduced the need for anchors in the slanted crosshead end. The bridge construction was completed in 2016.

A similar study was performed for a precast concrete pier cap of a curved bridge in the United States. It was shown that the weight of the cap could be reduced from 123 tons to 89 tons

and the amount of post-tensioning could be reduced. The pier cap was changed from a 60-in.-wide rectangle to a 24-in.-wide inverted tee with bottom flange ledges that could be used to eliminate independent shoring of the main girders at the piers.

Lesner Bridge in Virginia Beach, Virginia

The first half of the Lesner Bridge in Virginia Beach, Va., was opened in late 2016. ASTM A1035-CS reinforcement was substituted for stainless steel (Fig. 4). The design utilizes a yield strength of 75 ksi rather than the 60 ksi proposed for the stainless steel. Using the higher strength of ASTM A1035-CS alloy in the deck and substructure, significant savings due to simplified details and construction requirements were achieved.

Bridge Decks

ASTM A1035-CS alloy has been used for the deck reinforcement for the Circle Drive Bridge in Saskatoon, Canada, (Fig. 5) and for several bridges in Virginia. Research for the Virginia Department of Transportation[4] found that a deck constructed using ASTM A1035-CS alloy reinforcement with a ½ in. reduction in concrete cover and one bar size smaller than a conventional deck using Grade 60 reinforcement will perform similarly. A demonstration project is planned.

Conclusion

High-strength steel reinforcing bars with high resistance to corrosion are available on the market and have been used on bridge structures to reduce congestion, speed up construction, and improve service life.

References

1. Shahrooz, B. M., R. A. Miller, K. A. Harries, and H. G. Russell. 2011. *Design of Concrete Structures Using High-Strength Steel Reinforcement*. NCHRP Project Report 679. Washington, DC: Transportation Research Board.
2. Darwin, D., J. Browning, M. O'Reilly, and L. Xing. 2007. *Critical Chloride Corrosion Threshold for Galvanized Reinforcing Bars*. Project Report ZC-24-2. Lawrence, KS: University of Kansas Center for Research Inc.
3. Burke, N. 2014. *Reinforcing Steel Comparative Durability Case Studies and 100 Year Service Life Cost Analysis Report*. Kalamazoo, MI: Tourney Consulting Group LLC.
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6. AASHTO (American Association of State Highway and Transportation Officials). 2014. *AASHTO LRFD Bridge Design Specifications*, 7th ed., customary U.S. units. Washington, DC : AASHTO.

How Are We Doing?

Learning from the National Bridge Inventory

by Hank Bonstedt

Mayor Ed Koch of New York City during his tenure in the 1980s famously used to ask "how are we doing?" to get feedback from his constituents. As marketing managers in the prestressed concrete industry we always want to know the same thing: are we making progress?

But rather than simply ask people their opinions, I wanted to bring a more measurable analysis to this question. Since good and reliable market and trend projections rely on the appropriate selection of information, we need to ensure that sample size and design, as well as useful information items (that is, base data), are taken into account.

For analyses of highway bridges, the Federal Highway Administration compiles a significant amount of data on all of the nation's bridges in the National Bridge Inventory (NBI) database, which is prepared by the states according to a standard Recording and Coding Guide. For each bridge, this results in more than 115 items that are organized on a Structure Inventory and Appraisal sheet.

While the purpose of this effort is to have a "...complete and thorough inventory, so that an accurate report can be made to Congress" and to provide the data necessary to "...produce Defense Bridge and Federal Emergency Management Agency (FEMA) reports" it also contains the answer to our question.

We were interested to learn from the National Bridge Inventory database the number of bridges built each year and the distribution of the total number of bridges among the various road systems (Fig. 1).

We only considered bridges constructed or reconstructed after 1950. The reason for this limitation is that not all material alternatives were available prior to that time (Fig. 2).

We also can see how prestressed concrete bridges, since their first use in the United States, which happened in 1950 with the Walnut Lane bridge in Philadelphia, Penn., have been playing an ever-increasing role in meeting the bridge construction needs of the public.

The gains of prestressed concrete bridges become especially notable when seen as a percentage of the total bridge construction and reconstruction market (Fig. 3).

Such continuous market penetration over 65 years could not happen solely on the basis of low initial costs; it must also be explained in terms of the quality and durability of this type of bridge design and construction.

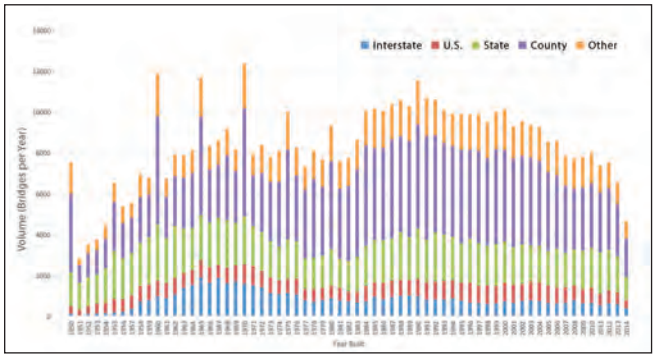

Figure 1. Number of bridges constructed by road system and year completed. All Figures: Hank Bonstedt.

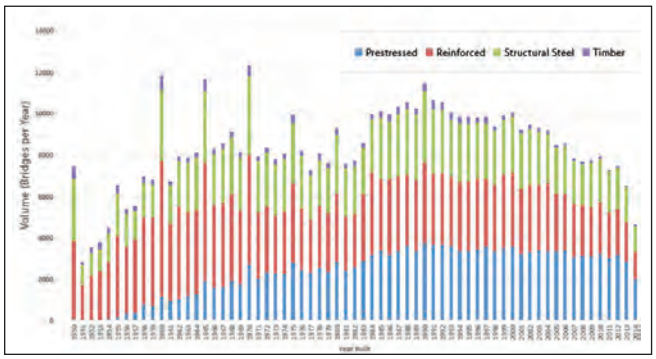

Figure 2. Number of bridges constructed by material and year completed.

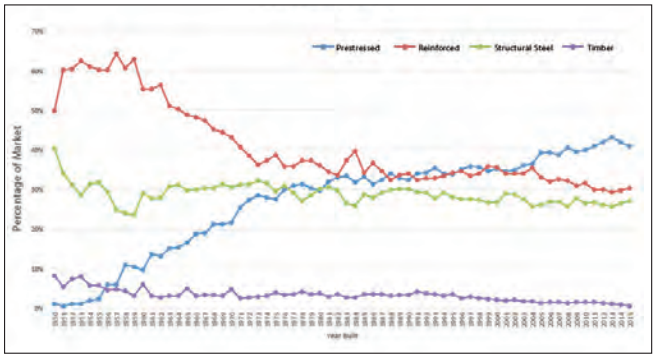

Figure 3. Percentage of bridges constructed by bridge type. Percentage is calculated based on the number of reported bridges completed in a given year.

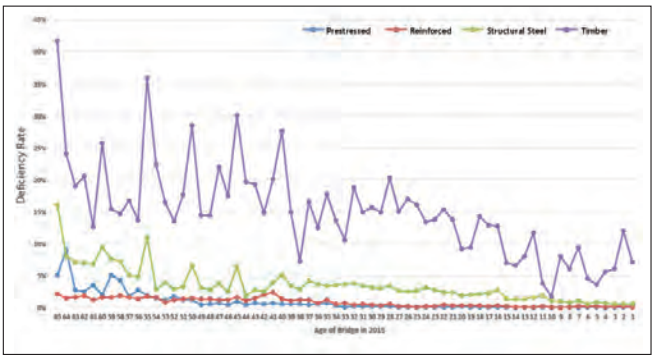

Figure 4. Overall rates of deficiency for all road systems by material and age of bridge.

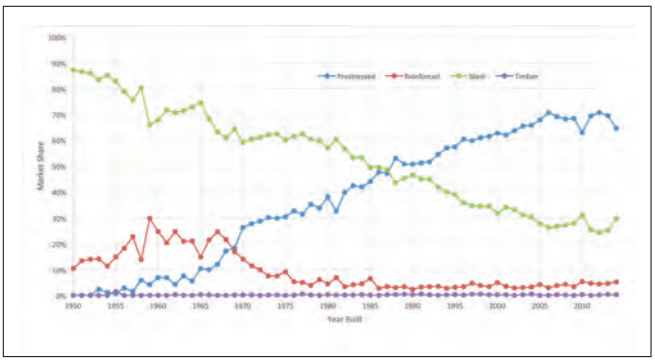

Figure 5. Percentage of bridges constructed by bridge type for bridge spans between 100 and 150 ft.

For this exercise we considered only bridges that have deficiencies (Fig. 4) as the result of condition ratings of 4 or less for deck, superstructure, and substructure, or an appraisal rating of 2 or less for structural condition. Deficiencies resulting from waterway adequacy or approach roadway alignment were not considered. These levels were established because a uniform level of urgency for remedial action is necessary.

With the development of more efficient beam sections, innovation in steel strands, and developments in high-performance concrete, it was also of interest to see how we are doing on the basis of market share for the main spans of a variety of bridges (Fig. 5).

So, to answer our question: the prestressed concrete industry is indeed making progress!

Hank Bonstedt is the former executive director of the Central Atlantic Bridge Association.

EDITOR'S NOTE

The analysis of National Bridge Inventory (NBI) data to compare the performance of different bridge materials was first considered in a master's thesis by Claude Napier, formerly with VDOT and FHWA. Drs. Kenneth Dunker and Basile Rabbat built on this work in an article published in the PCI Journal *in 1992. The Portland Cement Association then produced several reports characterizing market share and performance using NBI data that were written by Drs. Reid Castrodale and Shri Bhide. Finally, Hank Bonstedt published an article in* Concrete International *in October of 1998.*

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.

IN THIS ISSUE

http://www.pci.org/Project_Resources/Project_Profiles/Profile_Pages/Construction_of_100m_Single_Span_Batu_6_UHPC_Bridge/?terms=uhpc
This is a link to a profile of the BATU 6 bridge, which utilized ultra-high-performance concrete to achieve a 100-m-long single span. The bridge is mentioned in the Concrete Bridge Technology article on page 28 and was the recipient of the 2016 PCI Design Award for Best International Transportation Structure.

https://www.osha.gov/silica/
This is a link to information on the OSHA rule regarding respirable crystalline silica in the construction industry that is the topic of the article on page 10.

https://www.osha.gov/silica/SilicaConstructionRegText.pdf
This link is to the OSHA rule 1926.1153 on respirable crystalline silica in the construction industry.

http://www.aspiremagazinebyengineers.com/i/697527-summer-2016/49
This is a direct link to the article in the Summer 2016 issue of *ASPIRE*™ that explains the OSHA rule on respirable crystalline silica in the construction industry.

http://www.earthcam.com/client/caltrans/antlersbridge/index2.php
This is a link to current and archived photos of the Antlers Bridge featured in the Project article on page 24 of this issue.

http://www.dot.ca.gov/dist2/projects/antlers.htm
This link connects to the Caltrans project website for Antlers Bridge and contains photos, route re-alignment, schedule, etc.

http://maine.gov/mdot/sml/
This is a link to the Maine Department of Transportation website for the Sarah Mildred Long Bridge Replacement project currently being constructed by Cianbro Corporation, the contractor featured in the article on page 6.

http://aspirebridge.com/magazine/2007Winter/Penobscot.pdf
This is a direct link to the Winter 2007 *ASPIRE* article on the Penobscot Narrows Bridge constructed by Cianbro Corporation, the contractor featured in the article on page 6.

http://www.dura.com.my/
This link is to the DURA® website and gives the history of ultra-high performance concrete (UHPC) as well as descriptions of recent projects using their proprietary UHPC. DURA® is mentioned in the Concrete Bridge Technology article on page 28.

https://www.fhwa.dot.gov/innovation/everydaycounts/edc_4/uhpc.cfm
This is a link to the Federal Highway Administration website, which presents the benefits of using UHPC for the connections of prefabricated bridge elements. The website also provides access to informative videos and webinars.

https://www.fhwa.dot.gov/publications/research/infrastructure/structures/hpc/13060/13060.pdf
This is a direct link to *Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community* (Publication No. FHWA-HRT-13-060).

http://www.cement.org/for-concrete-books-learning/concrete-technology/concrete-design-production/ultra-high-performance-concrete
This is a link to the Portland Cement Association website that provides a basic explanation and material properties of ultra-high-performance concrete.

http://www.wmschultz.com/portfolio/accelerated-bridge-replacements/
This link is to a website that contains construction photos of the bridges that were replaced and are the subject of the project article on page 12.

http://www.crsi.org/Resources/technical/PDF/CRSI-Specialty_Steel_Product_Guide.pdf
This is a link to the Concrete Steel Reinforcing Institute's *Product Guide for Specialty & Corrosion-Resistant Steel Reinforcement*, which provides information for specification, fabrication, estimating, detailing, and placement of steel reinforcing bars specified for improved corrosion resistance, the subject of the Concrete Bridge Technology article on page 33.

https://oldcastleprecast.com/pressrelease/omega-bridge-sections-used-at-carter-machinery-caterpillar-site/
This is a link showing a proprietary short-span precast concrete bridge section that combines substructure and superstructure into a single piece.

Bridge Research

NEW http://www.epoxyinterestgroup.org/index.cfm/_api/render/file/?method=inline&fileID=A1B192D7-0D7D-9150-827A227745A92ECD
This is a link to *Summary of Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks,* which is a summary of an extensive research project funded by the Federal Highway Administration and Kansas Department of Transportation.

NEW http://www.iowadot.gov/bridge/ibrc_projects/mmfx_paper.pdf
This is a link to the report of a research project using MMFX reinforcement that was conducted at Iowa State University.

NEW http://www.nap.edu/download/24689
This is a link to *Control of Concrete Cracking in Bridges*, a synthesis report recently published by the National Cooperative Highway Research Program (NCHRP), which provides information on methods used to control concrete cracking in bridge superstructures and substructures, and on the influence of cracking on long-term durability.

A PROFESSOR'S PERSPECTIVE

STRUT-AND-TIE MODEL

Concrete bridge design by STM

by Dr. Oguzhan Bayrak, University of Texas at Austin

The eighth edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*, with substantial revisions in regard to applying the strut-and-tie model (STM), will be published in 2017. This edition of the AASHTO LRFD specifications places an increased emphasis on designing concrete structures with STM and clearly delineating B-regions from D-regions. Article 5.7, devoted to the design of B-regions, states the following:

> *Where it is reasonable to assume that plane sections remain plane after loading, regions of components may be designed for shear and torsion using either the sectional model as specified in Article 5.7.3 or the strut-and-tie method as specified in Article 5.8.2.*

This implies that STM can be used in lieu of the sectional design provisions. It is also worth noting the introductory sentence in Article 5.8, which is devoted to the design of D-regions:

> *Refined analysis methods or strut-and-tie method may be used to determine internal force effects in disturbed regions such as those near supports and the points of application of concentrated loads at strength and extreme event limit states.*

By these excerpts, it is obvious that all components of a concrete bridge can be designed using STM. Most certainly, bridge substructure components, such as pile caps and bridge bents, are prime candidates for design by STM. The introduction of loads by bridge beams and geometric discontinuities seen in some bent caps, such as inverted-tee caps, render such bridge elements as D-regions almost in their entirety. Following this line of thought, and starting about two years ago, I began teaching bridge substructure design by STM in our concrete bridge design class at the University of Texas. My teaching efforts, in this regard, greatly benefited from decade-long STM research, development, and implementation efforts funded by the Texas Department of Transportation.[1,2]

Students in the Ferguson Structural Engineering Laboratory at the University of Texas at Austin observe a reinforcing bar cage being placed into a form. Photo: David Birrcher and Robin Tuchscherer.

The starting point that I use in my bridge design class relates to some field problems and performance issues encountered in designing D-regions by using sectional design methods. It is true that in many cases the use of legacy sectional methods produces reasonable bridge bent designs. It is also true that there have been a number of cases in which the use of small pot bearings and associated stress concentrations underneath those bearings have created field issues. Similarly, I am aware of cases in which large quantities of stirrups used in the bent caps were not providing the benefits calculated in sectional designs because direct strutting of the load from bearings to supporting columns was the primary load-transfer mechanism. Providing clear explanations of the observed field problems and how those problems could have been avoided by using STM proved to be a great starting point in my classes. The following excerpt, taken from the commentary of the AASHTO LRFD specifications (C5.8.2.1), serves to let the designer know about some of the aforementioned performance issues in a concise manner.

> *Traditional section-by-section design is based on the assumption that the reinforcement required at a particular section depends only on the independent values of the factored section force effects* V_u, M_u, *and* T_u *and does not consider the manner in which the loads and reactions are applied which generate these sectional forces. The*

traditional method further assumes that the shear stress distribution is essentially uniform over the depth and that the longitudinal strains will vary linearly over the depth of the beam.

Perhaps the most important challenge in teaching bridge design by STM relates to shifting students' focus from the development of sectional force diagrams. Instead of having students design for those sectional effects by using legacy design methods, we want them to take a more holistic view of the element that is being designed. For example, rather than having to worry about flexural design and shear design in ways that can be viewed as being compartmentalized, the focus has to be shifted to identifying load paths that can be used in transferring loads from their respective points of application to supports/foundations. Flexural design, shear design, and reinforcing bar anchorage checks are all implicit when designing by STM, in addition to nodal stress checks under bearing pads and all other critical locations. Once a design by STM is complete, all aspects of design have been individually and collectively considered.

After overcoming the challenge outlined previously, students taking my class develop sufficient mastery of the technical aspects of structural design by STM. They work on a team project to go through a project-based learning experience, where the student teams build structural elements in our structures laboratory that they have designed by STM. Subsequently, the teams run structural tests on the elements they previously designed and fabricated such that they can observe the actual load paths, as evidenced by structural cracks and reinforcing bar strains. Ultimately, the student teams compare the experimentally observed load paths to those assumed in their original design. In this way, the circle of learning is complete.

The fact that STM forces structural engineers to think through each and every detail, as loads get transferred from their point of application to the foundations, is probably the most important attribute of this method. Carefully thought-out structural details not only help improve the load-carrying capacity of an element, but also improve the in-service performance. As we *aspire* to design bridges to last a century—while being mindful of our natural resource consumption, good structural details, and better optimized designs—structural designs by STM will undoubtedly gain increasing levels of importance. Stay well, until the next article.

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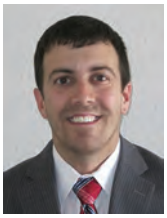
2. Williams, C., D. Deschenes, and O. Bayrak. 2012. *Strut-and-Tie Model Design Examples for Bridges: Final Report*. Report No. FHWA/TX-12/5-5253-01-1. Austin, TX: Texas Department of Transportation.



One Step Ahead: FHWA Investigates Commercially Available UHPCs

By Dr. Zachary B. Haber, Genex Systems, Dr. Igor De La Varga, SES Group, and Dr. Benjamin A. Graybeal, Federal Highway Administration

Advances in concrete technology—such as high-strength steel, microfiber reinforcement, superplasticizers, gradation optimization, and supplementary cementitious materials—began to be packaged together into a new generation of cementitious composite materials in the 1970s and 1980s. In the 1990s, this new class of materials was brought to market and has become known as ultra-high-performance concrete (UHPC).

Today, UHPC is being adopted for a variety of different bridge construction and rehabilitation applications, including 100% UHPC structural elements, bridge deck overlays, jackets for columns and driven piles, and field-cast connections between prefabricated bridge elements. This last application has proven to be a common entry point for owners and an extremely popular solution across the United States and Canada.[1] Figure 1 depicts several applications where UHPC provided a solution to a design- or construction-related challenge.

The first North American deployment of UHPC in a bridge was in Canada in 1997; it would almost be a decade until the first U.S. bridge was constructed using UHPC in 2005. Now, just over a decade later, the growth in the total number of bridges constructed using this advanced material has increased significantly (Fig. 2). In fact, some state transportation agencies have or are planning to integrate UHPC into their standard practices and details.

As Demand Grows, FHWA Supplies Knowledge

As the demand for UHPC-class materials grows, so will the potential opportunities for suppliers of construction materials. These include current suppliers of UHPC-class

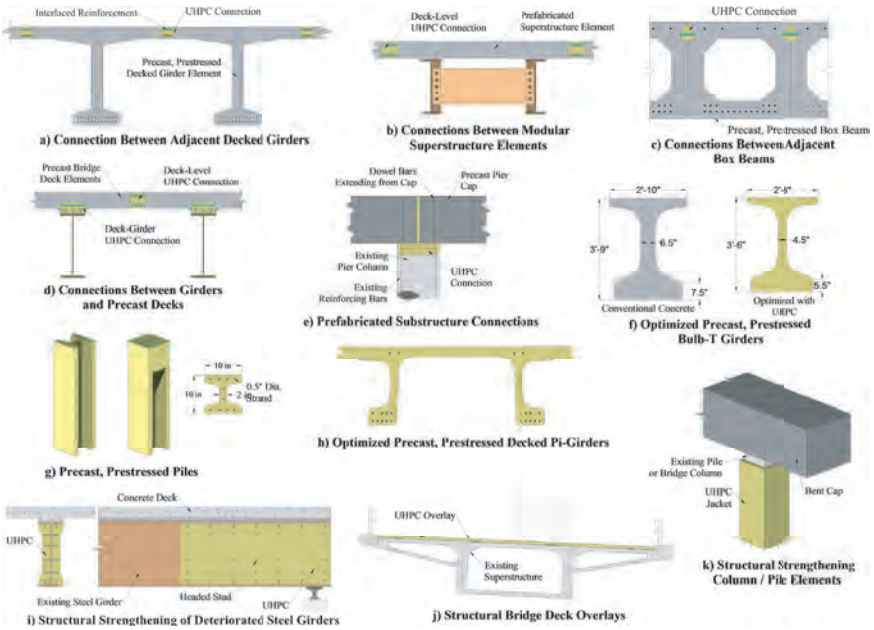


Figure 1. Bridge design and construction solutions using ultra-high-performance concrete. All Figures: Federal Highway Administration.

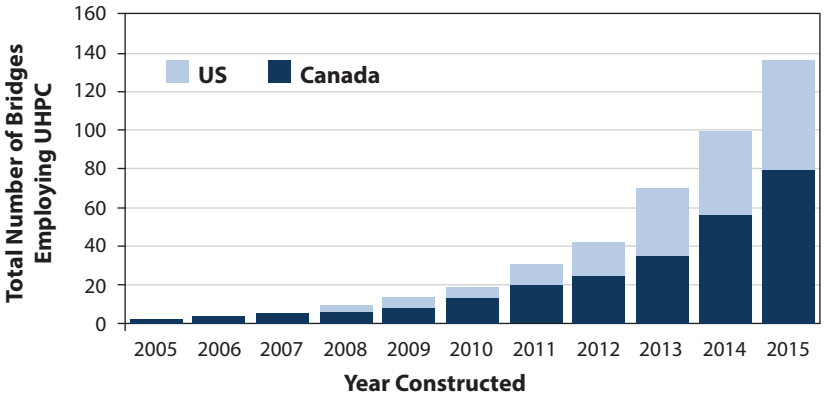


Figure 2. Chronology of bridge construction in North America with ultra-high-performance concrete.

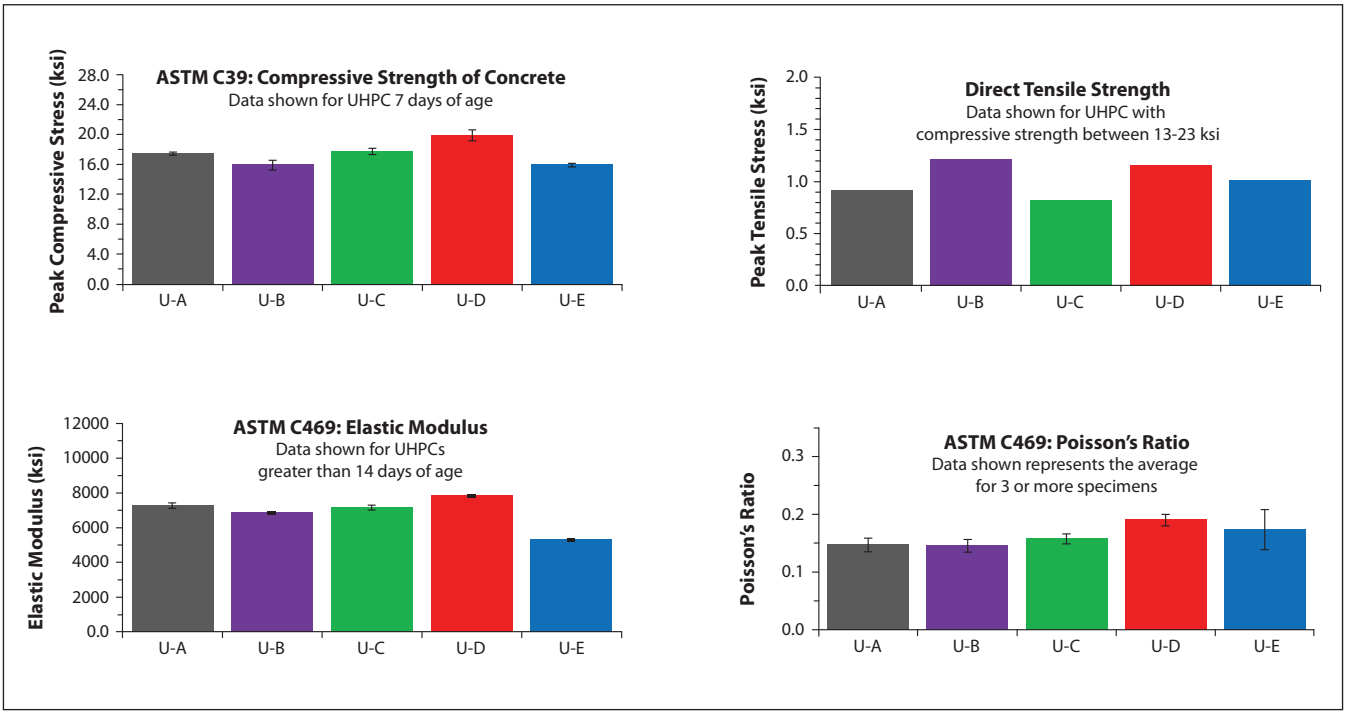


Figure 3A. Limited summary of test results on five different classes of ultra-high-performance concretes.

materials, emerging suppliers looking to bring a new product to the North American market, or small businesses looking to develop a locally-sourced product. As the demand for UHPC-class materials increases, so does the demand for knowledge. That is, the demand for a better understanding, from a general perspective, of the mechanical and durability properties of materials being marketed as "UHPC-class."

To fill this knowledge gap, researchers at the Federal Highway Administration's (FHWA) Turner-Fairbank Highway Research Center (TFHRC) executed an ambitious experimental study on five different commercially available materials that are marketed as UHPC-class. The goal of the research was to provide the bridge engineering community with a more comprehensive set of properties for this class of materials, which in turn could facilitate broader use within the bridge sector. Five materials, referred to as U-A through U-E, were tested. The experimental program included the following tests and associated test methods:

- Compressive Strength: ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*
- Modulus of Elasticity and Poisson's Ratio: ASTM C469, *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*
- Splitting Tensile Strength: ASTM C496, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*
- Direct Tensile Strength: Per test methods developed at FHWA's TFHRC
- Shrinkage: ASTM C157, *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*
- Compressive Creep: ASTM C512, *Standard Test Method for Creep of Concrete in Compression*
- Flowability: ASTM C1437, *Standard Test Method for Flow of Hydraulic Cement Mortar*
- Fresh Height Change: ASTM C827, *Standard Test Method for Change in Height at Early Ages of Cylindrical Specimens of Cementitious Mixtures*
- Set Time: ASTM C403, *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*
- Freeze-Thaw Resistance: ASTM C666, *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*
- Chloride Penetration: ASTM C1202, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*
- Surface Resistivity: AASHTO T358, *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*
- Bond to Concrete in Flexure: modified from ASTM C78, *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*
- Interface Bond Strength of UHPC to Substrate Concrete: ASTM C1583, *Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method)*
- Bond to Steel Reinforcing Bars: as described by Yuan and Graybeal[2]
- Behavior in Prefabricated Bridge Deck Connections: as described by Haber and Graybeal[3]

The researchers at TFHRC proportioned, mixed, and placed each material according to the manufacturer's specified procedures and conducted tests using both the manufacturer's recommended steel-fiber volume fraction and also a 2% volume fraction, which is common for field-cast UHPC applications. Researchers also cured the materials to simulate the conditions of field-cast UHPC. Heat or stream treatments were not applied. They mixed, placed, and cured the specimens under ambient laboratory conditions.

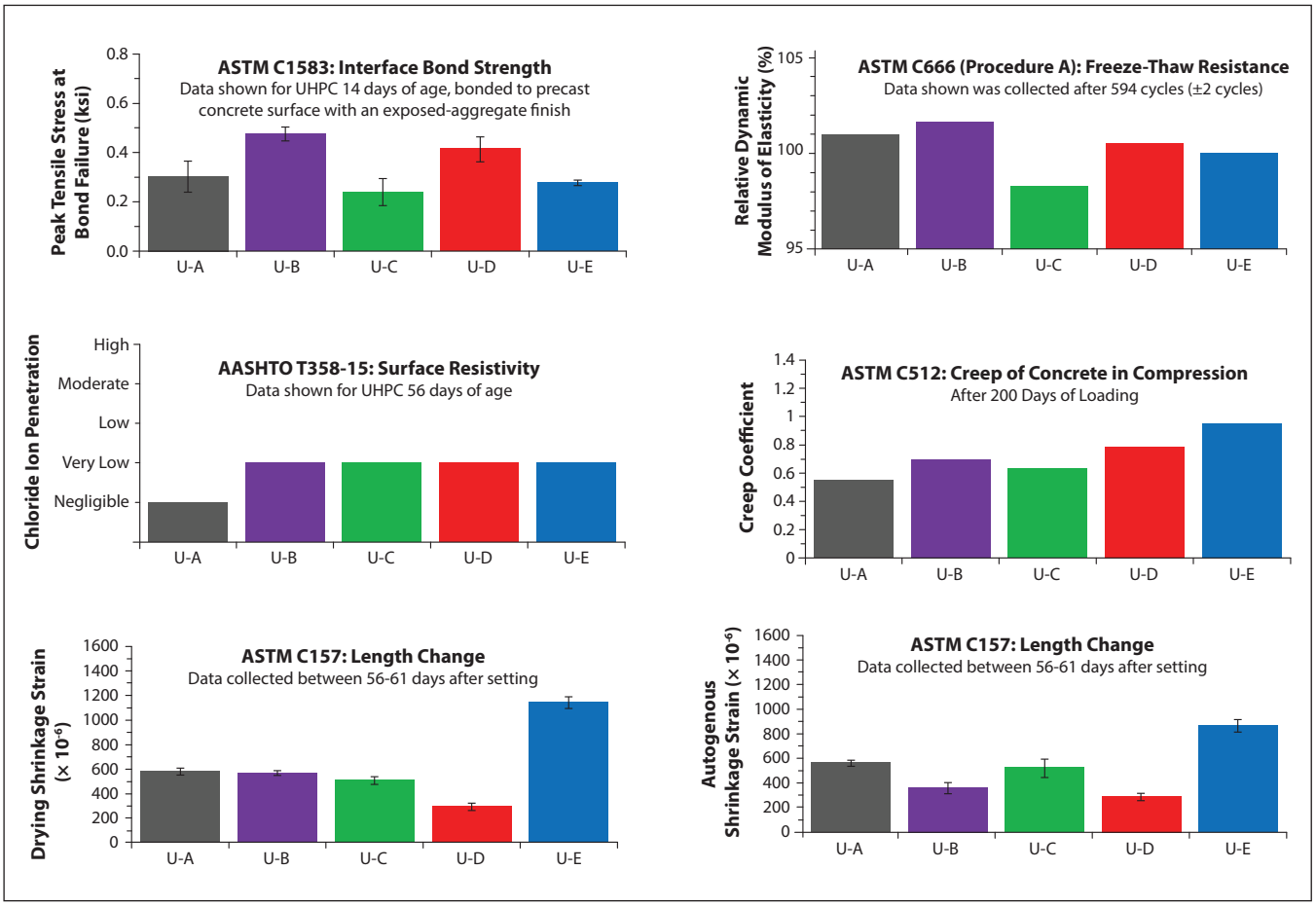


Figure 3B. Limited summary of test results on five different classes of ultra-high-performance concretes.

Findings

UHPC is known to have excellent durability properties, bond well to hardened concrete and deformed steel reinforcing bars, and have good resistance to compressive creep and good dimensional stability. As far as mechanical properties are concerned, FHWA defines UHPC to have a "*…compressive strength greater than 21.7 ksi and sustained post-cracking tensile strength greater than 0.72 ksi.*"

Figures 3A and 3B show a limited summary of results. With the exception of one type of UHPC (U-E), which did not exhibit compressive strengths greater than 21.7 ksi, the materials exhibited compression and tension properties consistent with FHWA's definition of a UHPC-class material. Each material exhibited very good durability in terms of surface resistivity and freezing and thawing resistance. The dimensional stability of the materials, which is also commonly associated with durability properties, as measured by ASTM C157, indicated a wide range of shrinkage properties among the different UHPCs. Lastly, the UHPCs exhibited some variation in the ability to bond to hardened concrete. However, this was likely a function of each material's fresh-state rheology, among other material properties. That is, materials exhibiting less flowability tended to exhibit lower bond strengths. A complete set of results and findings are currently being compiled into a final report and will soon be available to the bridge design and construction community.

Moving Forward

As the construction materials and bridge design communities strive to develop innovative and useful solutions using UHPC, FHWA intends to continue in its roles as both a technical resource and a visionary leader. Beyond assisting with the assessment of newly available UHPC materials, FHWA is initiating the process of developing a guide specification for bridge design and construction using UHPC. Through partnerships with state transportation agencies and the American Association of State Highway and Transportation Officials, the guide specification is expected to be an inflection point in the expanding use of UHPC for highway infrastructure.

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Post-Tensioned Concrete: An Inherently Durable System

by Dr. Andrea Schokker, University of Minnesota Duluth

I teach courses in prestressed concrete and bridge design, and I am freshly reminded each semester about the inherent durability we have in our post-tensioned (PT) concrete bridge elements. While the phrase "belt-and-suspenders approach" may be overused, I think it truly defines a PT system. The steel strand is separated from aggressive agents, such as moisture and chloride, by the concrete, the PT duct, and grout (or other material or coating). Additionally, we have seen active development in each of these areas over the past 15 years, particularly in PT bridge systems. I've outlined the progression of each component below with a focus on a grouted PT system.

Concrete and Steel

Low-permeability concrete with high-quality placement has become far more common, particularly in the quality-controlled, tight-tolerance environment of a bridge casting operation. We know far more about concrete materials and admixtures than we did a decade ago and the knowledge base continues to expand each year.

Quality concrete, combined with the active prestressing force from the steel PT tendon, provides the foundation for a highly durable structure. With today's low-permeability concrete, cracks are the primary path for corrosive agents to reach the steel. The precompression of PT concrete keeps cracks from forming under service loads and forces any cracks that might form to close after an overload is removed. This combination of high-strength steel strand and concrete brings the best out in both materials for a solution that is customized (through PT tendon layout) to the expected loads.

Duct and Anchor Protection

The PT duct and anchorage protection system has been revolutionized over the past 15 years. As a PhD student with Dr. Jack Breen at the University of Texas at Austin in the late 1990s, I was part of a team studying a wide array of options for improving durability of PT systems, including duct types, grout types, anchor protection, strand coatings, galvanized strands, and prestress level.[1–3] Most of the specimens contained the standard system at the time: a galvanized duct with duct-taped splices and attachments to the end trumpet, no end cap, and a nonshrink grout pourback in the anchor recess.

The Putnam Bridge in Washington County, Ohio, is a testament to the timeless aesthetic of concrete bridges. Photo: Julia David, Barr & Prevost.

Otay River Bridge, San Diego County, Calif. Photo: Mike Palhegyi.

Walsh Group built the Allegheny River Bridge, which features twin cast-in-place concrete segmental bridges with 532-ft-long main spans. Photo: FIGG.

Grouting was often done through an empty strand hole in the anchor head and venting, when done, was not always sealed with durable details. None of these would be considered good practice today in a PT bridge.

The PT system manufacturers responded quickly to the need for a more robust system to protect the tendon. In the concrete industry, change is often slow, but in this case we quickly saw the introduction of a number of new systems: watertight robust plastic duct, watertight mechanical duct and trumpet connections, leave-in-place plastic end caps, positive shut-off vents, and trumpets designed with a grout port that would also be accessible for inspection.

PT Grout

PT grout has come a long way in the past 15 years. The standard grout at the time of my PhD research was a 0.45 water–cement ratio, plain-cement-and-water grout that sometimes included an expansive admixture intended to help fill potential void areas (but was found to cause more issues than it helped[4]). We recognized the need for a high-performance material that had appropriate antibleed characteristics and a thixotropic (thick when static, less viscous when agitated) nature along with tests to measure antibleed properties. These early thixotropic grouts coming out of our research were water, cement and a thixotropic (gelling) agent suspended in a superplasticizer. The industry then moved to prepackaged versions for wider distribution that contained additional additives.

While the grouting material was changing, the Post-Tensioning Institute was also updating its grouting specifications to include state-of-the-art testing and implementation methods, and the American Segmental Bridge Institute started its grouting certification training course in 2001. Specifications, training, and materials have continued to develop since that time—all three of which are necessary for a quality end product. A cementitious grout when properly mixed and injected (including proper venting and low-point injection when possible), provides a compatible material for a PT concrete element including a high-pH environment for protection of the prestressing steel.

Summary

The PT system is inherently a multilayer protective environment that utilizes steel and concrete to their maximum potential for strength, ductility, crack control, durability, and overall resiliency. For this reason, many PT structures are in excellent condition today that were built prior to the advancements in PT durability that have been implemented over the last 15 years.[5]

We need to continue to train the workers who place the systems and continue to develop tests that are field friendly to ensure consistent quality. With today's improved materials, systems, and training, PT bridges are a robust, state-of-the-art solution for durable, high-performance bridges.

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Dr. Andrea Schokker is a professor and head of the Department of Civil Engineering at the University of Minnesota Duluth.

Confined Space Considerations for Bridges

A practical look at mitigating hazards due to confined spaces

by John Kinkle, PCL Civil Constructors Inc.

Confined spaces encountered during construction and maintenance of bridges present safety hazards in the construction industry that require mitigation. The construction industry's understanding of these physical and atmospheric hazards has increased in recent years, allowing the industry to mitigate hazards associated with confined spaces and reduce related worker issues. The hazards associated with confined spaces, such as engulfment, oxygen deficiency/enrichment, flammable gases, and other physical hazards, are severe and can have dire consequences if not addressed properly.

On May 4, 2015, the Occupational Safety and Health Administration (OSHA) issued a new standard for construction work in confined spaces, which became effective August 3, 2015. The new standard, Subpart AA of 29 CFR 1926, is intended to "prevent construction workers from being hurt or killed by eliminating and isolating hazards in confined spaces at construction sites similar to the way workers in other industries are already protected" by the confined-spaces standard. An electronic copy of the full regulatory text of the *Confined Spaces in Construction* standard can be found at https://www.osha.gov/confinedspaces/1926_subpart_aa.pdf.

As defined by the standard, a confined space has a limited means of entry and exit, is large enough for a worker to physically enter it, and is not intended for regular or continuous occupancy. A permit space, one requiring a permit, "is a confined space that may have a hazardous atmosphere, engulfment hazard, or other serious hazard, such as exposed wiring, that can interfere with a worker's ability to leave the space without assistance."

Given their enclosed shapes, segmental concrete box-girder bridges are an obvious context in which to review confined spaces. However, given the above definitions of what constitutes a confined space, all bridge types will have some element of confined spaces and they should be identified during the project-planning phase. Once identified, these safety concerns can be mitigated through proper planning and best practices.

What's New?

OSHA has identified five key differences between the new *Confined Spaces in Construction* standard and the general industry standard. The five new requirements follow:

1. More detailed provisions requiring coordinated activities when there are multiple employers at the worksite. This will ensure that hazards are not introduced into a confined space by workers performing tasks outside the space. An example would be a generator running near the entrance of a confined space causing a buildup of carbon monoxide within the space.
2. Requiring a competent person to evaluate the worksite and identify confined spaces, including permit spaces.
3. Requiring continuous atmospheric monitoring whenever possible.
4. Requiring continuous monitoring of engulfment hazards. For example, when workers perform work in a storm sewer, a storm upstream from the workers could cause flash flooding. An electronic sensor or observer posted upstream from the worksite could alert workers in the space at the first sign of the hazard, giving the workers time to evacuate the space safely.
5. Allowing for the suspension of a permit, instead of cancellation, in the event of changes from the entry-conditions list on the permit or an unexpected event requiring evacuation of the space. The space must be returned to the entry conditions listed on the permit before reentry.

For contractors that already abide by the general industry standard, the new confined-spaces standard for construction activities will likely not have a significant effect on their procedures, aside from the differences described previously.

Designing for Confined Space

The design stage is an excellent time to begin thinking about potential confined spaces both during bridge construction and during regular maintenance inspections. Each bridge type presents a unique set of circumstances during bridge inspection. Temporary and permanent hatches for construction should be considered to maximize ingress and egress of construction workers as well as to increase ventilation. This also aids the maintenance and inspection teams down the road. Simple considerations for the installation of electrical outlets for ventilation fans along with interior lighting can aid the inspection or maintenance team in their duties as well.

Confined Space during Construction

Planning is key to identifying upcoming hazards associated with confined spaces and ensuring that those hazards are communicated properly to the frontline worker. One best practice is for the contractor performing the evaluation to identify a space as a permit-required confined space until determined otherwise. The number of workers, their varying familiarity with the constantly changing hazards, and working in close proximity to one another are hazards addressed by the new standard and

Enclosed outer cells were identified as confined spaces, separately from other interior sections of the bridge segments. Photo: Kenneth Payne.

Signs help identify confined spaces to workers or inspectors not directly involved with an operation. Photo: Andrew Mahoney.

Introduction of a gas-powered concrete vibrator requires a review of the space to determine if it is a confined space. Photo: John Kinkle.

should factor into the space-identification process. Signage that identifies potentially confined spaces is a great way to protect crews from unknowingly entering a confined space.

The nature of construction means that possible confined spaces are constantly changing. In segmental concrete bridge construction, the inside of a form traveler is a constantly changing environment, where short sections of a bridge are constructed with many different trades occupying the same space at overlapping intervals, each introducing a different set of hazards. A confined space may not be present at the start of a segment cycle, but if thermal blankets are used to enclose the space for heating, and the same space is then occupied by a gas-powered concrete vibrator, the environment needs to be reevaluated to confirm that it is safe for all workers present. If the exhaust is found to be creating a hazard, one solution would be switching to electric vibrators using external power sources.

The inside of a bridge, where crews may be applying an elastomeric coating to post-tensioning anchors, is a likely example of a permit space, given the enclosed environment and any health hazards associated with the product. Specific conditions will warrant varying controls, but entry and exit points to the areas where hazardous work is occurring should be clearly marked. Those involved should be well trained on the hazards. Those occupying the same confined space must also understand how the environment has changed so they can take the proper precautionary measures.

Whether the confined space is considered a permit-required or nonpermit space, emergency rescue procedures must be built into the construction plan, as it may be difficult to extract an injured person from the space. An emergency response plan should be developed and reviewed with local fire departments for the most efficient and safest way to rescue an injured employee. Considerations to discuss include access to the employee, such as high-angle rescue, or rescue from a snooper truck, truck ladder, aerial lift, or crane and rescue basket; atmospheric hazards, such as oxygen, carbon monoxide, hydrogen sulfide, or lower explosive or lower flammable limits, and any exposure above the permissible exposure level; and physical hazards, such as lighting, slips, trips, falls, and electric shock. Prior to workers entering a confined space, the lead contractor must coordinate and communicate emergency response procedures, OSHA requirements, and the responsibilities of the confined space supervisor, attendant, and entrants with all employees, subcontractors, and owners.

Summary

There is an OSHA standard for construction work in confined spaces that has different requirements from the one for general industry. It is vital that the construction industry be proactive and institute a thorough program to keep employees safe and to mitigate the hazards due to confined spaces.

John Kinkle is a project manager with PCL Civil Constructors Inc. in Raleigh, N.C.

EDITOR'S NOTE

The information required by the new standard is taken from the OSHA webpage "Confined Spaces in Construction – Frequently Asked Questions" found at https://www.osha.gov/confinedspaces/faq.html.

AASHTO LRFD Bridge Design Specifications: Combined Shear and Torsion

by Dr. Oguzhan Bayrak, University of Texas at Austin

In the Summer 2016 issue of *ASPIRE*, this column provided an introduction to design for torsional resistance using the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*. This article is a follow-up to that discussing design for combined shear and torsion.

The commentary of the eighth edition of the *AASHTO LRFD Bridge Design Specifications* acknowledges that shear stresses stemming from torsion and those caused by shear are additive on one side of a member and act in opposite directions on the other side of the same member. Naturally, transverse reinforcement is designed for the side where the effects are additive. The commentary states that the loading that causes the highest torsion differs from the loading that causes the highest shear, in most cases. The commentary also indicates that it is only necessary to design for the highest shear and its concurrent torsion, and the highest torsion and its concurrent shear. However, as a design simplification, designers may find it convenient to design for the highest torsion combined with the highest shear, despite the fact that those load effects do not occur concurrently for the same load combination.

With this guiding principle in mind, for solid sections the longitudinal reinforcement shall be proportioned to satisfy *AASHTO LRFD Bridge Design Specifications* Eq. 5.7.3.6.3-1 (with the familiar variables not discussed herein):

$$A_{ps} f_{ps} + A_s f_y \geq \frac{|M_u|}{\phi d_v} + \frac{0.5N_u}{\phi} + \cot\theta \sqrt{\left(\left|\frac{V_u}{\phi} - V_p\right| - 0.5V_s\right)^2 + \left(\frac{0.45 p_h T_u}{2A_o \phi}\right)^2}$$

The transverse reinforcement design for solid sections is also addressed by the AASHTO LRFD specifications. For such sections, considerable redistribution of shear stresses may occur, as stated in the commentary. To make some allowance for this favorable redistribution, the commentary deems it safe to use a root-mean-square approach in calculating the nominal shear stress for solid cross sections. Where torsion is to be considered, the AASHTO LRFD specifications provide Eq 5.7.3.4.2-5 for this purpose:

$$V_{eff} = \sqrt{V_u^2 + \left(\frac{0.9 p_h T_u}{2A_o}\right)^2}$$

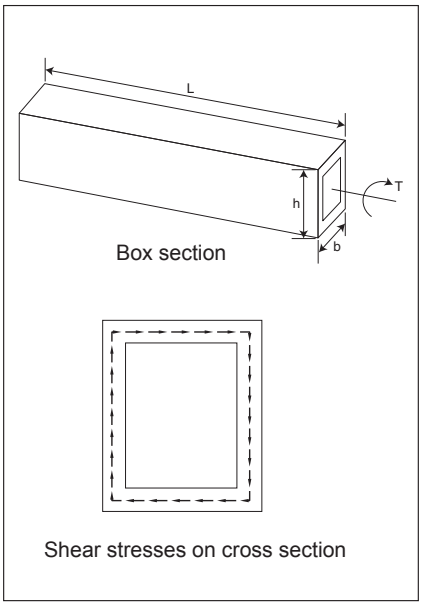
In calculating the effective shear force, the 0.9 comes from 90% of the perimeter of the spalled concrete section, an approximation similar to 0.9 times the effective section depth in flexural calculations used to estimate the internal lever arm. For combined shear and torsion, the effective shear V_{eff} replaces the V_u term in Eq. 5.7.3.4.2-4:

$$\varepsilon_s = \frac{\left(\frac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{ps} f_{po}\right)}{E_s A_s + E_p A_{ps}}$$

Similar to solid sections, the specifications and commentary include guidance for designing hollow sections subjected to combined shear and torsion.

The specifications also provide an alternative for the designer by stating that, instead of the method discussed previously, the resistance of members subjected to "shear combined with torsion may be determined by satisfying the conditions of equilibrium and compatibility of strains and by using experimentally verified stress-strain relationships for reinforcement and for diagonally cracked concrete." Furthermore, the specifications allow the use of a three-dimensional strut-and-tie model for complex stress states, such as those that exist in combined shear and torsion problems, as well as loading conditions that may induce shear in secondary directions.

Circularity torsion



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