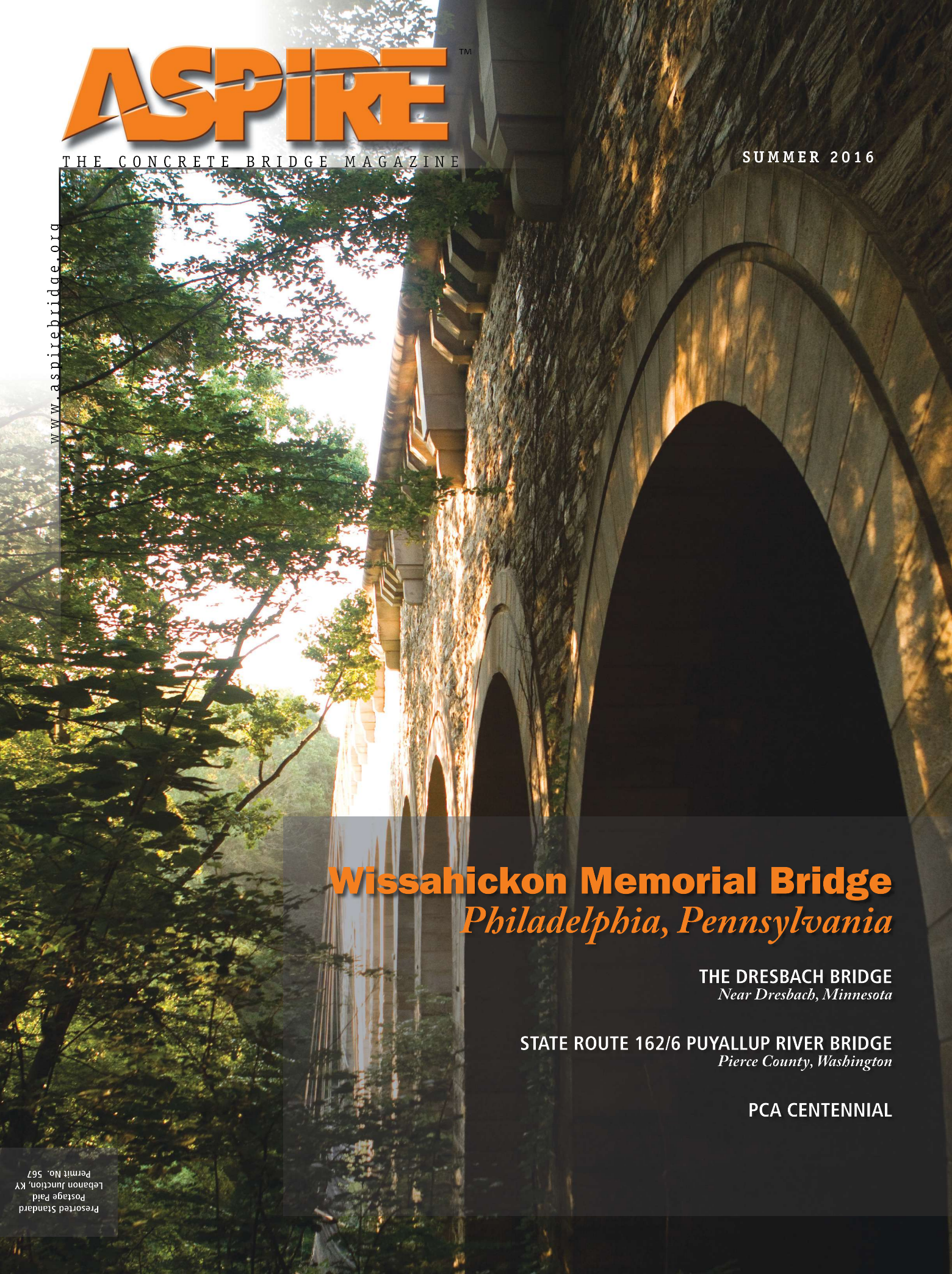
ASPIRE™

THE CONCRETE BRIDGE MAGAZINE

SUMMER 2016

www.aspirebridge.org



Wissahickon Memorial Bridge
Philadelphia, Pennsylvania

THE DRESBACH BRIDGE
Near Dresbach, Minnesota

STATE ROUTE 162/6 PUYALLUP RIVER BRIDGE
Pierce County, Washington

PCA CENTENNIAL

Presorted Standard
Postage Paid
Lebanon Junction, KY
Permit No. 567

SHAPING THE FUTURE OF BRIDGES

Timeless.
Sustainable.
Best Value.

FIGG®

www.figgbridge.com
1 800 358 3444

Bridges that integrate community visions, improve quality of life, capture the spirit of the people being served, and focus on mobility and sustainability in aesthetically pleasing form.

CREATING BRIDGES AS ART®

1| New I-35W Bridge, MN
2| I-91 Brattleboro Bridge, VT, *Rendering/Under Const.*
3| I-280 Veterans' Glass City Skyway, OH
4| I-93 Leonard P. Zakim Bunker Hill Bridge, MA
5| Harbor Bridge, TX, *Rendering/Under Const.*
6| Honolulu Rail Transit Project Kamehameha Highway, Hi
7| Sarah Mildred Long Bridge, ME, *Rendering/Under Const.*
8| Selmon Expressway, FL

5.2016

Photo with Rendering: FIGG.

Photo: Washington State Department of Transportation.

Photo: Portland Cement Association Archives.

Features

Departments

Photo: FIGG.

Advertisers Index

EDITORIAL

Photo: PCI.

Are We Now Foolishly Preemptively Deselecting a Material or Solution?

William Nickas, *Editor-in-Chief*

My last two editorials have garnered some interesting feedback and I want to further explore how to embrace innovation in the bridge construction and project delivery arena. For me, my thoughts on this topic changed with the Summer 2014 Perspective by Dr. Benjamin Graybeal. In that *ASPIRE*™ article, he outlined a real, pressing challenge for the industry, which is to find the "transformational innovations" and locate "broad-based advancements in our foundational technologies." He then suggested four key strategic opportunities: crack mitigation in structural concrete; alternate concrete matrices; performance under combined loadings; and emerging classes of concrete with enhanced material properties. This made me think about how we might be able to discover and embrace these innovations in the industry using techniques with which we are already familiar.

Early in my career, I worked on a few interesting value-engineering studies. These studies were based on brainstorming sessions in which there are no bad ideas, no barriers, and no criticizing allowed. After the initial brainstorming, alternates were studied to determine viability based on questions such as:

1. Does it serve the intended function?
2. Does the alternate save money or time?
3. Will this lower the life-cycle costs?
4. Will this create a better life-cycle assessment?
5. And more recently, is this alternate a more resilient solution?

Very often these early-stage studies reduce project team's biases. These concepts from the value-engineering studies can also be used to implement more-innovative ideas/solutions into the whole transportation industry. Indeed, there is a history of this occurring.

John Dick, the founding executive editor of *ASPIRE*, wrote a response to Dr. Henry Russell's perspective in the last issue on the history of this publication. In that letter, John wrote of the innovation in the industry in the last 10 years that have already occurred. A couple key points from John regarding change are as follows:

1. At an AASHTO SCOBS meeting in 1988, industry was called upon to explain an agenda item to adopt the new family of bulb-tee-shaped bridge girders. He said it was not an easy assignment. John recalls a discussion that ensued. States discussed who were using concrete strengths other than the traditional f'_c = 5 ksi and f'_{ci} = 3.5 ksi in their designs. Only a small hand full were permitting as much as 5.5 ksi; one dared to say 6 ksi!
2. Now look at 2006. Without needing to elaborate, the industry was in transition with new beam shapes, larger and stronger strands, self-consolidating concrete, higher strength concretes, shallower sections, longer spans, new admixtures and ingredients, and the list goes on.
3. At that same time, 10 years ago, along came the idea for *ASPIRE*. It has served as a vehicle for sharing these concrete bridge experiences and industry advancements.
4. Peer pressure is amazing and *ASPIRE*'s role must be to continue to be the vehicle to dramatically reveal what the leaders in the bridge industry are accomplishing with modern materials and design.

In closing I will add one more idea to the above value-engineering discussion and John's reflections on influencing change. Maybe a different comparison or basis is needed when we decide to look at change such as contrasting ultra-high-performance concrete (UHPC) with structural steel. Steel weighs 490 lb/ft^3 and costs \$1.35 per fabricated pound. This would equate to a comparative cost of \$17,860/yd^3 of concrete. Just maybe using UHPC at \$1500 to \$3000/yd^3 for more than wall, column, and deck joint connections is not out of the question when one looks at the total bridge system.

ASPIRE authors from the private sector and governmental agencies are telling over 40,000 students and peers to look at what's happened with new code provisions, accelerated bridge construction, and new concrete materials. Let's not "preemptively deselect [UHPC]" by revisiting other strategies to implement. First costs of the material may not seem as high, if one considers the benefit of smaller construction and delivery equipment. Perhaps this could be recognized with better mixing equipment, lighter/thinner solutions, and sandwiched components. Then perhaps, reengineering our whole concrete bridge system and delivery like Dr. Voo did in Malaysia would not seem so radical (see page 36). Let's start addressing changes in our concrete foundational technologies and the four key topics in Graybeal's strategic opportunities with this one innovative concrete material.

Editor-in-Chief
William Nickas • wnickas@pci.org

Managing Technical Editor
Dr. Reid W. Castrodale

Contributing Editor
Dr. Henry G. Russell

Program Manager
Nancy Turner • nturner@pci.org

Associate Editors
Emily B. Lorenz • elorenz@pci.org
Craig A. Shutt

Layout Design
Tressa A. Park
Casey Braun

Cover
The Wissahickon Memorial Bridge in Philadelphia, Pa., on which Modjeski and Masters was the lead engineer in 1927, was rehabilitated in 2010 by the firm. Photo: Modjeski and Masters.

Ad Sales
Jim Oestmann
Phone: (847) 838-0500 • Cell: (847) 924-5497
Fax: (847) 838-0555 • joestmann@arlpub.com

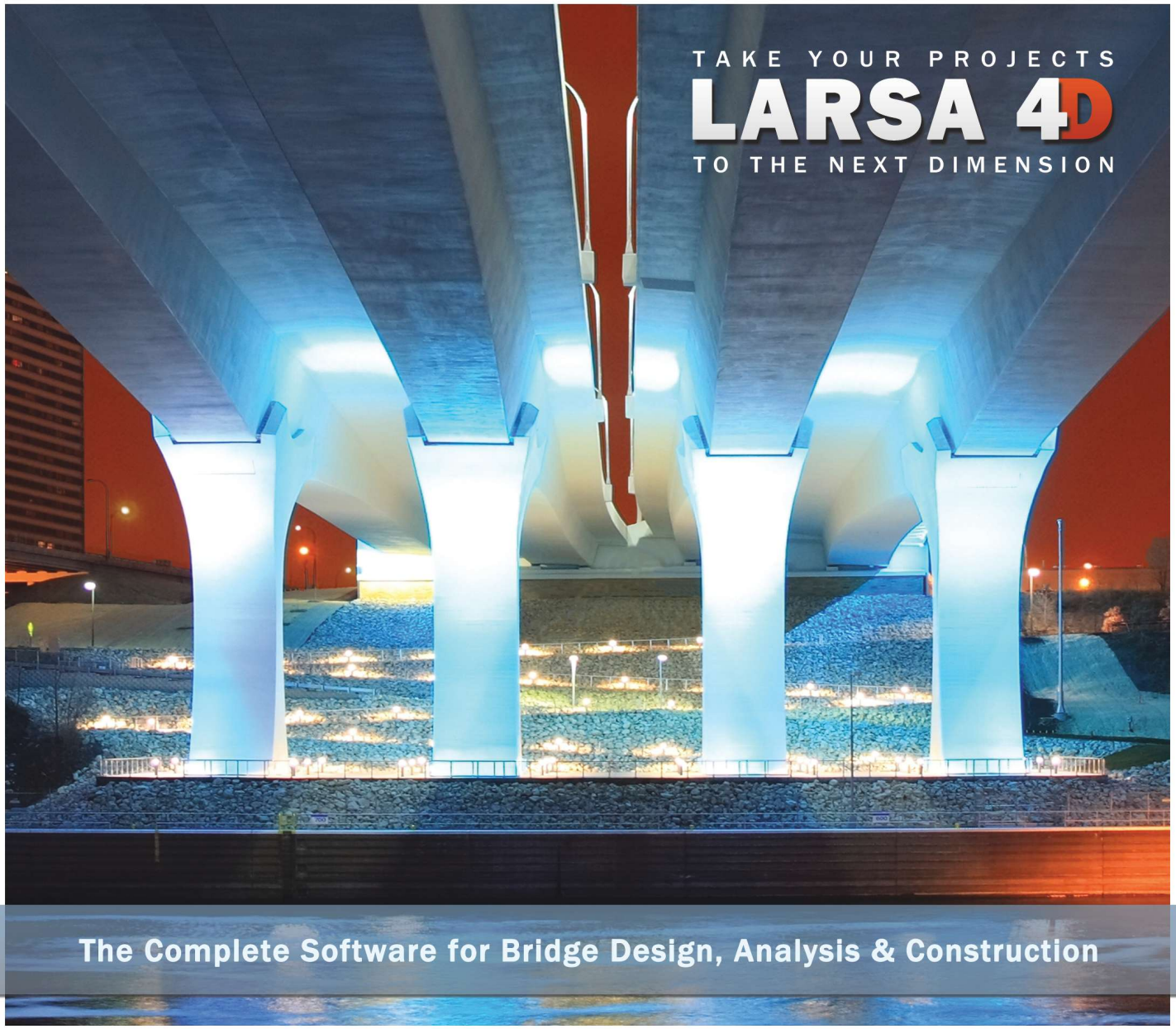
Reprints
Nancy Turner • nturner@pci.org

Publisher
Precast/Prestressed Concrete Institute
Robert Risser, President

Postmaster: Send address changes to *ASPIRE*, 200 W. Adams St., Suite 2100, Chicago, IL 60606. Standard postage paid at Chicago, IL, and additional mailing offices.

ASPIRE (Vol. 10, No. 3), ISSN 1935-2093 is published quarterly by the Precast/Prestressed Concrete Institute.

If you have a suggestion for a project or topic to be considered for *ASPIRE*, please send an email to the address below
e-mail: info@aspirebridge.org



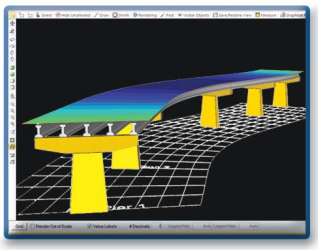
BRIDGE SERIES

4D BRIDGE PLUS | 4D BRIDGE | 4D BRIDGE pLT

LARSA 4D BRIDGE SERIES integrates all features into a single application providing process efficiency and delivering time savings. With innovative tools to support the life of a bridge project from design to construction, LARSA 4D is relied upon by bridge engineering professionals to deliver the most trusted solutions from short-span to demanding long-span bridge projects.

With 15-years of development guided by client input, LARSA 4D Version 8.0 continues to lead the industry with advanced modeling techniques that were infeasible just a decade ago. With new features coming in 2016 for composite construction, fine-mesh modeling, load rating and a new concrete bridge design module, LARSA 4D Version 8.0 meets the demanding needs of aging infrastructure and the modeling of complex materials to intuitively determine the behavior of bridges.

LARSA 4D VERSION 8.0



Coming Summer 2016

- Concrete Bridge Design Module
- New Tendon Editor
- Composite Construction
- 64-Bit Analysis Engine
- Extended AASHTO Load Rating

1-800-LARSA-01
for a free trial license visit www.LARSA4D.com

I-35W Bridge
FIGG Engineering Group

CONTRIBUTING AUTHORS

Dr. Oguzhan Bayrak is a professor at the University of Texas at Austin. Bayrak received the University of Texas System Board of Regents' outstanding teaching award in 2012 and was inducted into the university's Academy of Distinguished Teachers in 2014.

Dr. Benjamin Graybeal is the team leader for bridge and foundation engineering within the U.S. Federal Highway Administration's Office of Infrastructure Research. He also leads the structural concrete research program.

Frederick Gottemoeller is an engineer and architect, who specializes in the aesthetic aspects of bridges and highways. He is the author of *Bridgescape*, a reference book on aesthetics and was deputy administrator of the Maryland State Highway Administration.

Paul Kinderman is the state bridge and structures architect for the Washington State Department of Transportation Bridge and Structures Office in Olympia, Wash. He is a member of the American Institute of Architects and the TRB Bridge Aesthetics Subcommittee.

Dr. Dennis R. Mertz is professor of civil engineering at the University of Delaware. Formerly with Modjeski and Masters Inc. when the *AASHTO LRFD Specifications* were first written, he has continued to be actively involved in their development.

Matt Rochon is a senior bridge engineer for the Washington State Department of Transportation Bridge and Structures Office in Olympia, Wash. He is also a candidate for architectural registration and a member of the American Institute of Architects.

CONCRETE CALENDAR 2016–2017

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

July 18-20, 2016
First International Interactive Symposium on UHPC
Des Moines Marriott
Des Moines, Iowa

July 25-29, 2016
PCA Professors' Workshop
PCA Campus
Skokie, Ill.

July 31-August 4, 2016
AASHTO Subcommittee on Materials Annual Meeting
Hyatt Regency Greenville
Greenville, S.C.

August 28-31, 2016
AREMA 2016 Annual Conference & Exposition
Hilton Orlando
Orlando, Fla.

September 1, 2016
fib Symposium 2017
Call for papers deadline

October 3, 2016
2016 PCI Design Awards
Submission deadline

October 12-15, 2016
PCI Committee Days and Membership Conference
Loews Chicago O'Hare
Rosemont, Ill.

October 23-27, 2016
ACI Fall 2016 Concrete Convention and Exposition
Marriott Philadelphia
Philadelphia, Pa.

November 8-9, 2016
ASBI 28th Annual Convention
Long Beach Convention and Entertainment Center
Westin Long Beach Hotel
Long Beach, Calif.

November 21-23, 2016
fib Symposium 2016
Cape Town, South Africa

January 8-12, 2017
Transportation Research Board 96th Annual Meeting
Walter E. Washington Convention Center
Washington, D.C.

January 17-20, 2017
World of Concrete 2017
Las Vegas Convention Center
Las Vegas, Nev.

READER RESPONSE

Editor,
Your editorial in the Spring 2016 issue of ASPIRE™ *is spot on. One thing that I think is paramount is that contract drawings are easily constructible (at least most easily for the task at hand) and that the shop drawings be submitted and reviewed in a very timely manner. We often get held up in either not submitting in a timely manner or the review takes too much time. Ahead of this is submitting and getting answers on RFIs. The better and quicker the drawings become, the better chance we have to meet schedule, have a successful project, have a happy owner, and have a repeat customer. I do appreciate your tireless efforts for PCI and our industry.*

Pat Hynes
Knife River Prestress
Harrisburg, OR

THE QUIET COMPANY

Modjeski and Masters builds its expertise with concrete bridges through continuing innovations and making its first acquisition in 123 years

by Craig A. Shutt

Well known for the steel bridges it has designed since its founding in 1893, Modjeski and Masters (M&M) had gained less attention for its advancements with concrete designs. That work is now coming to the fore thanks to innovative concrete designs and its acquisition in 2015 of Summit Engineering Group, which specializes in segmental and spliced-girder concrete designs.

"The bridge industry typically views the firm's specialty as being one of designing, rehabilitating, and inspecting complex steel structures," explains Michael F. Britt, senior vice president and director of business development for the Mechanicsburg, Pa.-based firm. "While our project portfolio is dominated by being the designer of record for numerous steel bridges, M&M has also developed innovative concrete designs that have introduced new concrete bridge technology for new and rehabilitated bridges throughout the nation."

"We've been the quiet company when it comes to talking about our accomplishments with concrete bridges," says Barney T. Martin Jr., president/CEO. "In fact, throughout our history, there have been years when we designed more square feet of concrete bridges than steel."

The Bronco Bridge in Denver, Colo., a 371-ft-long, three-span, rigid-frame bridge, features spliced precast, pretensioned and post-tensioned concrete U-girders, as well as precast concrete curved piers, integral abutments, and precast concrete deck panels. All Photos: Modjeski and Masters.

Precast Concrete Deck Panels Grow

One key area where the firm has innovated has been with precast concrete deck panels, which it first used in 1980 on the Bayview Bridge over the Mississippi River at Quincy, Ill. A key driver for its design was the need to complete the work in 18 months. The project became the first cable-stayed bridge in the country to feature precast, post-tensioned concrete deck panels. "The end result was a more evolved and robust structure," says Britt.

More recently, the firm used precast concrete panels to replace the existing reinforced concrete deck and railing in approach spans on the Ambassador Bridge connecting Detroit, Mich., with Windsor, Ontario, Canada. At one time the longest suspension bridge in the world, it now has precast concrete panels in the 5600-ft-long approach spans of the 7500-ft-long structure.

'We expect precast concrete deck panels will be used more often in the future.'

"We expect precast concrete deck panels will be used more often in

the future," Britt says. "We use them frequently in rehabilitation projects to better control construction while leaving lanes open to traffic." Not only can the panels be installed quickly, often at night, but they are manufactured under factory-controlled conditions. "Vibrations from traffic can encourage cracking in cast-in-place concrete while curing," he points out. "Precast concrete is fabricated under ideal conditions, so it minimizes that concern."

Summit 'A Great Fit'

Innovative designs using concrete will no doubt continue after the acquisition of Littleton, Colo.-based Summit last fall. Its addition creates "a symbiotic relationship that brings to the table aspects that round out our expertise and bolster our capabilities," says Martin "It's a great fit." Gregg A. Reese, president of Summit, agrees. "Our partnership opens up new markets for our small, niche-based firm that weren't available before."

The agreement resulted from serendipity, Martin notes. "We developed a strategic plan that included a goal of expanding our concrete projects, and we knew of the work Gregg was doing at Summit." At the same time, Reese was looking to expand his business into new markets. "We all realized what a good fit merging our firms would be, so the deal went together very quickly."

Reese opened Summit in 1995 and saw it evolve over time, reacting to changes in the construction market. For the past 10 years, the firm has focused on providing construction-support services for contractors. "There's not a lot of competition in that niche, and we focused on local markets," Reese explains. He positioned the firm as a 'rent-an-engineer' program at a time when construction companies were transitioning to using outside consultants. "That opened a real opportunity for us later when contractor-driven designs became more popular."

It also provides an ideal fit with M&M. "Modjeski and Masters has strong relationships with its owner clients, with 90% of its business coming from repeat customers, whereas our strongest relationships have been with contractors," says Reese. "We know how to work with different clients and understand their needs, so we can provide any services required."

The Bronco Bridge in Denver, Colo., was value-engineered, virtually eliminated traffic disruption, and finished on budget.

U-Girder Designs

One area where Summit's expertise expands M&M capabilities is with spliced, post-tensioned precast concrete U-girders. That work began about 15 years ago through close cooperation with the Colorado Department of Transportation, which has led the nation in using those types of beams. "We were engaged for constructability reviews as well as value-engineering designs and even complete designs," Reese says. "We went from being a support firm to becoming more of a design firm, although we continued to focus on contractor services."

The projects have included Ramp G at the Parker Road Interchange in Aurora, Colo., in 2000 and the Ramp K Bridge in Denver, Colo., in 2004. "Those projects really brought to light the advantages of this bridge type," says Britt. "The structural shape is suitable for complex interchange projects with both long and short spans, and it creates an attractive structure. It also offers significantly shorter fabrication times, reduces the number of joints and bearings, and offers extensive span continuity."

A prominent project to take advantage of this design involved replacing the Bronco Arch Bridge in Denver. The 371-ft-long, three-span, rigid-frame bridge consists of spliced precast, pretensioned and post-tensioned concrete U-girders; precast concrete curved piers; integral abutments; and full-depth precast concrete deck panels. It was completed in 2013, 2 months ahead of the original plan due to value-engineering into this format. It also virtually eliminated traffic disruption and finished on budget.

'The U-shaped cross section provides robust enough capacity to erect them on curves, opening new possibilities for efficient designs.'

Although the Bronco Bridge's spans were from 95 to 148 ft long, creating U-girder bridges in the 250-ft-long range has become common, and they can easily reach 300 ft, Reese says. "The U-shaped cross section provides robust enough capacity to erect them on curves, opening new possibilities for efficient designs."

Modjeski and Masters provided preliminary engineering for concrete and steel alternatives and also reviewed the final plans for the concrete alternate design prepared by the design-build team for the Carey Avenue Bridge across the Susquehanna River at Hanover Township, Pa.

The three-span Wadsworth Light-Rail Transit Bridge in Denver. Colo., features a design that ensured that spliced, post-tensioned, precast concrete girders could support two rail lines and a new transit station and platform above the street.

U-girders will grow to be more common, Martin adds. "They offer many benefits for interchange designs. It is becoming extremely difficult for other options to defeat. The precast concrete option wins every time." Those advantages are especially apparent in value-engineering designs, says Reese. "We find that by redesigning a steel bridge, the contactor can pay our engineering and start-up fees with the savings they generate and still come out ahead over the steel design."

"It's a very exciting field," Martin says. "U-girders open interchange construction to a total-precast concrete solution that works well. We design each bridge to fit its location using the best materials available—but the steel guys are worried."

That expertise led Reese to the chair of the Curved Bridge Committee at the Precast/Prestressed Concrete Institute (PCI). "We discuss better design guidelines for engineers and other techniques that will improve efficiency and simplicity," he says. "There is a lot of movement to advance and consolidate the technology, and PCI has been a big part of its growth. It's exciting."

M&M has long been involved with creating bridge specifications and standards. In the late 1980s, it led a team developing the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* and assisted departments of transportation in modifying their specifications to conform. "We're confident that the U-girder standards we've helped develop also will be approved in the near future," Britt says.

New Delivery Methods

M&M's expertise allows it to adapt to new delivery methods growing in popularity. "The entire delivery system is different today, with different types being used," says Martin. "As they change, we have to adapt to the unique needs of each client."

The firm was one of the first to work with Pennsylvania's alternate-delivery format, creating concrete alternatives when requested. An example is the Carey Avenue Bridge that crosses the Susquehanna River between Hanover Township and Plymouth Borough, Pa. M&M provided preliminary engineering for concrete and steel alternatives and also reviewed the final plan by the design-build team. The end result was a $27.5-million, four-lane, 2395-ft-long crossing consisting of 16 spans of prestressed concrete I-beams.

Today's increased focus on design-build projects plays well to the firm's expertise. "You have to be adaptable," says Reese. "Design-build offers an accelerated pace of construction, but it's a little more planned." That doesn't mean they disdain traditional design-bid-build projects, adds Martin. "We have experience representing both owners and contractors, depending on the project."

M&M also has worked efficiently in the newer hybrid form, Construction Manager/General Contractor (CM/GC), also known as Construction Management at Risk. "We find it to be more effective due to the continuous collaboration between the contractor, engineer, and owner," says Britt. "The owner never loses control of the design development. With design-build, once the initial plan is developed, a new team takes over with its plan. With CM/GC, the engineer follows the design all the way to final design."

Summit was part of the CM/GC-driven Wadsworth Bridge, which is a section of a light-rail extension connecting Denver

and Golden. The firm proposed a precast concrete, spliced bulb-tee girder alternative to the original steel-plate design due to the high cost of steel at the time.

"I really liked the CM/GC experience," Reese says. "It was a comfortable and very cooperative environment with the flexibility to do innovative things during the process to improve the project. It fostered partnership such that no additional schedule time was required to make the necessary modifications."

Public-private partnerships also are growing and adding new factors. "They put greater emphasis on durability and service life," Britt explains. "The total expense of operation and maintenance is more in the beginning. They require good, solid designs and constructability values, but they don't minimize expenses of materials at the cost of long-term durability."

The Wissahickon Memorial Bridge in Philadelphia, Pa., on which Modjeski and Masters was the lead engineer in 1927, was rehabilitated in 2010 by the firm, rehabilitating its original reinforced concrete arch design using colored concrete and strategic lighting to add aesthetic touches. The work won several awards from local and state preservation groups.

Rehabilitation Proliferates

M&M's long history sometimes brings it back to its original designs. "We always feel fortunate when we have a chance to extend a bridge's life for another generation," says Britt.

That experience occurs more often today, says Martin. "America's aging infrastructure and the unwillingness to absorb the high cost for new bridges has led many owners to look to repair structures." M&M offers an inspection service that can perform a cost-benefit study, make suggestions on key repairs as well as create designs to accomplish them.

"The needed repairs are often on a case-by-case basis, owner by owner, with few similarities," Martin notes. "A lot depends on how proactive the owner's maintenance program has been over the years and what construction techniques were being used at the time."

One example is the Wissahickon Memorial Bridge (also known as the Henry Avenue Bridge) over the Wissahickon Creek in Fairmont Park in Philadelphia, Pa. The structure consists of a reinforced concrete arch with a 300-ft-long span, which is faced with stone. Built in 1927 with M&M as the lead engineer, the company returned to renovate it in 2010, using colored concrete and strategic lighting to add to the aesthetic touches. Their preservation efforts won awards from the Preservation Alliance for Greater Philadelphia and the Pennsylvania Preservation Award for Excellence in Transportation.

M&M's 123 Years of Service

Modjeski and Masters (M&M) was founded by Ralph Modjeski (born Rudolf Modrzejewski), a Polish engineer who immigrated to America and opened his own firm in Chicago in 1893. He was joined in 1924 by Frank M. Masters. One of the first bridges they designed as M&M in the 1920s was the Clarks Ferry Bridge, featuring 15 reinforced concrete arches, each with a 140-ft-long span.

M&M operates nine regional offices primarily in the eastern United States, from its corporate headquarters in Mechanicsburg, Pa. The firm ranked No. 260 in the 2015 listing of top design firms by *Engineering News Record*, moving up 50 spots from 2014. Summit Engineering was the first acquisition in the company's history.

M&M also is looking to future bridge designs by continuing its innovative efforts with concrete projects. "Our work with U-girders and drop-in spans has led us to focus on ways to minimize expansion joints and bearings in projects, which are critical points," Britt says. "They are the first two elements to deteriorate, and our goal is to minimize or eliminate them. There is great potential for achieving that."

The firm's own evolution isn't complete either. The master plan that brought Summit into the fold is continuing to develop, with more acquisitions and collaborations planned, but Martin declined to name specifics. "There is more on the horizon, I can promise that," he says. "But we're not the kind of company that dictates its size and schedule for changes. We focus on the services we want to provide and what fits with our existing philosophy, and that leads us to grow the clients we serve and the employees we need to reach those goals."

Bridges and Public Art

Crime prevention through environmental design

by Paul Kinderman and Matt Rochon,
Washington State Department of Transportation

Graffiti removal costs are estimated at over $8 billion per year in the United States. It's generally considered disruptive to public safety and a barrier to economic potential. But when you think of the graffiti, do you think of public art as a deterrent? You will after learning about crime prevention through environmental design (CPTED).

Strategies for the Built Environment

CPTED is a multi-disciplinary tool aimed at deterring criminal behavior through environmental design. The method provides strategies that influence offenders and was formulated 45 years ago by criminologist Clarence Ray Jeffrey. Central to the theory is the notion of defensible space where people should see and be seen continuously. Strategies may be small scale, such as trimming shrubs that obscure police sight lines, or they may include an entire neighborhood where residences are oriented to ensure occupants can monitor street activity. We'll focus on just two strategies here: natural surveillance and natural territorial reinforcement.

Bridge engineers may recognize these terms from project urban design guidelines. These are common language in the lexicon of urban design and refer to natural surveillance and territorial reinforcement, respectively.

Natural Surveillance

Natural surveillance is often expressed as *eyes on the street* and relies on the placement of physical features and activities to maximize visibility. This fosters social interaction among legitimate users of the public areas. And when offenders observe this increased scrutiny, crime is deterred because it becomes too risky. Public fear is diminished when offenders can be observed, identified, and apprehended.

Maintenance repair of graffiti on Interstate 5 on ramp in Mount Vernon, Wash., prior to public art (left). Citizens typically consider graffiti disruptive to public safety and economic potential. Public art shows natural territorial reinforcement strategies at the same Interstate 5 on-ramp (right). Photos: City of Mount Vernon.

Crime is inversely related to the level of activity on the street.

Since crime is inversely related to the level of activity on the street, more people in a public setting leads to less crime. Increased pedestrian and bicycle traffic support this effort. And in transportation facilities, vehicular traffic is considered an aide to surveillance.

Typical natural surveillance elements in transportation work include trim landscape plantings, transparent noise walls, lighting with good color rendition, and designs that encourage high volumes of citizen use at all times.

Natural Territorial Reinforcement

Natural territorial reinforcement is another CPTED strategy that promotes the social control of public spaces. Two things happen when citizens acquire a vested interest in high-quality areas.

First, an increased sense of ownership encourages local residents to challenge offenders or report them to the police. Second, inappropriate users stand out and are easily identified. People must care about their territory before they're willing to intervene in, or report, crime.

Territorial ownership is created by well-maintained premises, which in turn communicates an active presence. And increased use, promoted by high-quality designs, attracts more people and leads to the perception of social control.
Typical natural territorial reinforcement strategies in transportation projects include community-based artwork, increased maintenance, and well-defined public areas. Surprisingly, and contrary to traditional law enforcement thinking, research has shown that trees are seen by citizens as creating significantly more attractive and safer spaces.

We'll look at a few examples. The urban settings will be familiar to bridge engineers all over the United States.

Example: Mount Vernon, Washington State

The city of Mount Vernon in western Washington State had an Interstate 5 on-ramp that was being tagged. It so happened that the mayor, Jill Boudreau, had a background in law enforcement. As a community service officer, she worked on the front lines of crime prevention. So when discussions started

with strategies to repair graffiti (and the challenge to civil order that it implied) the idea of public art as a deterrent was quickly vetted.

But the mayor already knew the strategy worked in her town. Just around the corner from the freeway ramp, the city already had one of those charming American classics. It was a small retaining wall with paintings of tulips, mountains, and blue sky. The little wall was as immaculate as the town. And it was not tagged (at least in part) because of the territorial component of CPTED. It's because locals created a sense of ownership and definition of public space.

Example: Spokane, Washington State

Old railroad bridges in downtown Spokane carry an Amtrak line. And every bridge had been tagged repeatedly. So the Spokane Arts Commission mobilized its Murals program. And eventually every railroad undercrossing in downtown received a mural, light-hearted wall sculptures, or even just a fresh coat of paint.

Conventional wisdom has it that graffiti artists respect the work of the muralists. So there's a tendency for the walls to be left alone by the taggers. And on the city's Murals website, you can read about activating underutilized areas and place-making.

Other examples

Other examples abound. And newly aware readers will now recognize them in their own neighborhoods. For instance, look at the Puyallup River Bridge south of Seattle, Wash. It shows a more grassroots approach. The river's trail runs under the bridge approaches and suffers the fate of blight. It's vandalized because it's a bit secluded (no natural surveillance). But territorial reinforcement principles come into play when the taggers pretty much leave the artist's fish mural alone.

Summary

How effective is CPTED? One meta-analysis in the United States found a decrease in robbery crimes between 30% and 84%.[1] Even though effective, CPTED does have its critics. For instance, some point to the word prevention and suggest deterrence is more accurate.

Railroad bridge in Spokane, Wash., demonstrating territorial reinforcement and tendency of taggers to respect public art. Photo: Washington State Department of Transportation.

Tagging of the Puyallup River Bridge pier demonstrating a lack of territorial reinforcement in a partially activated space. Photo: Washington State Department of Transportation.

Grassroots citizen effort showing territorial reinforcement under the bridge at the trail. Photo: Washington State Department of Transportation.

Others point to the surveillance component and fear it could lead to vigilantism. Or some simply ask: why not just use surveillance cameras? All are fair questions pointing to the complexity of the issue.

Are there other strategies? Sure. You can read a recent paper by Eck and Martinelli where you'll find correlations between concrete surface finish amplitude and incidents of graffiti.[2]

But CPTED has endured for decades as the prevailing theory; shared by both criminologists and urban designers. So until society solves the problems of disaffected youth tagging walls, you can look for this common sense and intuitive method to prevail. And for structural engineers, it might be helpful to just think of it like strut-and-tie analysis. It's intuitive, it's common sense, and there's a scientific underpinning.

So take a deep breath bridge engineering colleagues! The next time your project artist walks in the room please know that you're both working toward public safety. Because if we build bridges people care about, bridges with locally meaningful motifs and bridges with charm. . .then the public will protect them.

References

1. Casteel, Carri, and C. Peek-Asa. 2000. "Effectiveness of Crime

Prevention Through Environmental Design (CPTED) in Reducing Robberies." *American Journal of Preventive Medicine*, 18(4 Suppl): pp. 99-115. DOI: 10.1016/S0749-3797(00)00146-X

2. Eck, R., and D. Martinelli. 2014. "Assessment and Mitigation Measures for Graffiti on Highway Structures." *TRB Record*, 1642(5). DOI: http://dx.doi.org/10.3141/1642-05

References for further reading

Atlas, Randall (Ed). 2008. *21st Century Security and CPTED: Designing for Critical Infrastructure Protection and Crime Prevention*. CRC Press, Taylor & Francis Ltd., Milton Park Abingdon, UK, 500 pp.

Jacobs, Jane. 1961. *The Death and Life of Great American Cities*. Random House, New York, NY, 598 pp.

Jeffery, C. Ray. 1977. *Crime Prevention Through Environmental Design*. Sage Publications, Beverly Hills, CA, 351 pp.

Washington State Department of Transportation (WSDOT). 2015. *WSDOT Design Manual*, M 22-01.12, Chapter 950, Public Art. WSDOT, Olympia, WA.

AESTHETICS COMMENTARY

by Frederick Gottemoeller

I'm glad to see the recognition this article gives to the role of public art in bridge design. Having a background in architecture and urban design as well as engineering, many of these ideas are familiar. But, as the article points out, art's effect is more than just aesthetic enjoyment, as important as that is. Art's effectiveness in evoking Natural Surveillance and Natural Territorial Enforcement means significant reductions in vandalism and the costs of remediating it. To add to that list, public art can evoke significant civic pride and community solidarity when it is used to enhance spaces under bridge approaches and viaducts so that they are more amenable to civic uses. As I said in the Spring 2016 edition of *ASPIRE*™:

> "In recent years, with the growing public interest in urban living and making cities more livable, there has been new interest in taking advantage of the space under viaducts, and not just for organized parking. Parks and playgrounds and farmers' markets are all uses that are now occurring under viaducts."

In Hastings, Minn., the south approaches to the new US 61 Bridge over the Mississippi River cross over the town's historic shopping avenue, Second Street, with minimal vertical clearance. The space below the bridge had the potential to end up like so many others, dark, unpopulated and threatening, with consequent negative impacts on the shopping street. The first step toward avoiding that was to use a post-tensioned, cast-in-place, minimal-depth concrete slab for the structure. This maximized the vertical clearance under the structure and created a smooth and light colored underside which facilitated the penetration of daylight into the space under the bridge. The second step was to place the south abutment as far back as reasonable from the curb line in order to make the space under the bridge more useful for civic activities (Fig. 1). The third step was to place all piers outside the building lines for Second Street so that the "space of the street" was not narrowed as it passes under the bridge (Fig. 2).

The final step was to place a natural stone "mural" on the south abutment wall. This work depicts the history of Hastings in variously colored natural stones (Fig. 3). Contrary to the usual expectations, it was the result of a collaboration between the design-build contractor, an artist retained by the contractor, and the citizens advisory committee. The design-build contract required that the contractor find an artist who could develop a theme satisfactory to the committee. The artist proposed the historical mural of colored stone and the committee accepted it.

The south approaches have become a source of civic pride. Residents take visitors to see it, and the area under the bridge has become an important focus of the summertime historic car rallies that are a Hastings tradition. And it was all done in the context of a competitively bid, design-build process.

Figure 1. Weekend historic car rally on Second Street. Photo: Dale Thomas.

Figure 2. Daylight and space at the south abutment. Photo: Frederick Gottemoeller.

Figure 3. A visitor to Hastings exploring the mural. Photo: Frederick Gottemoeller.

The Dresbach Bridge

A bridge springs forth from nature

by Eric Breitsprecher, Minnesota Department of Transportation, and Courtney C. Oltman, Stephen E. Fultz, and John R. Dvorak, FIGG

Dual 508-ft-long spans over the main channel of the Mississippi River result in large navigational and recreational openings, and only one pier in the river that is away from the bank. All photos: FIGG.

The new Dresbach Bridge, which carries Interstate 90 (I-90) over the Mississippi River, is a highly utilized river crossing that serves as a gateway for regional and interstate needs and is an enhanced local connection for the adjacent communities. The replacement bridge connecting La Crescent, Minn., and La Crosse, Wis., addresses a significant Minnesota Department of Transportation (MnDOT) need and brings greater mobility to the area.

May 2016 view of the completed segmental main channel bridge looking east. The 1667-ft-long bridge was built from the above over the main channel of the Mississippi River.

The Dresbach Bridge is designed to exceed current structural standards and greatly improve roadway geometry on this important regional corridor. Bi-directional precompression of the superstructure from high-strength post-tensioning steel, high-performance concrete, stainless steel deck reinforcement, and integral wearing surfaces on all spans provide MnDOT with a highly durable bridge for long-term performance and far less future maintenance cost. Combined with the concurrent reconstruction of the adjacent Trunk Highway 61 (TH61)/I-90 interchange, the overall project improves safety, capacity, and access while replacing the outdated highway system with a long-life facility for MnDOT and the traveling public.

Aesthetically, the bridge serves as a beautiful companion to the pristine waters and recreational facilities of the Mississippi River. Located within the Upper Mississippi River National Wildlife and Fish Refuge, the Dresbach Bridge serves as a model for how a grand bridge structure can be developed with the community to exist harmoniously

profile

DRESBACH BRIDGE / NEAR DRESBACH, MINNESOTA

BRIDGE DESIGN ENGINEER: FIGG, Denver, Colo.

CONSTRUCTION INSPECTION: WSB, Minneapolis, Minn.

PRIME CONTRACTOR: Ames Construction, Burnsville, Minn.

PRECASTER: County Materials Corporation, Janesville, Wis.—a PCI-certified producer

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

with, and honor, the landscape and environment.

The existing bridge over the Mississippi River consisted of twin structures each supported by a 12-span, steel, two-girder system with a nonprestressed reinforced concrete deck. The twin-girder superstructure, while typical to the era, featured undesirable details that warranted replacement. Narrow shoulders below current standards made the bridge difficult to traverse and inconvenient for travelers. Emergency vehicles couldn't pass, space for disabled vehicles was non-existent, and routine maintenance required the bridge to be closed.

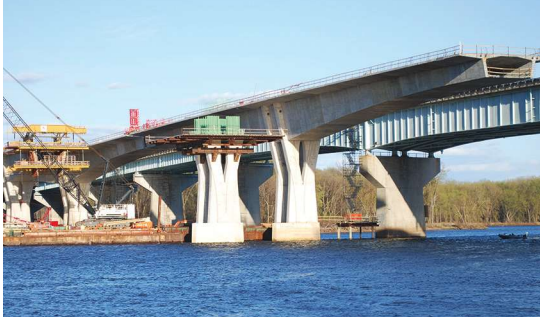
Bridge for the Future

A new, modern, high-performance, ecologically sensitive four-lane concrete bridge was designed to replace the deficient structure. Over the main channel of the Mississippi River, the new four-span bridge features twin, post-tensioned segmental concrete structures with two 508-ft-long main spans, built from above with form travelers in balanced cantilever. Building from above eliminated the need for large ground- and water-based equipment, allowed commercial and recreational river traffic to continue throughout the duration of construction unimpeded, and preserved the environment. Construction is kept to the smallest footprint possible to protect not only the environment, but also recreational facilities along the Minnesota bank, an adjacent rest area, and operations of U.S. Army Corps of Engineer's Lock and Dam No. 7 just upstream.

Beyond the main channel of the river, the east channel is significantly shallower, with a maximum depth of approximately 10 ft. While not commercially navigated, the east channel is a favorite fishing spot for many residents. The new east channel structure is comprised of twin 6-span units that are achieved through the introduction of 82-in.-deep prestressed concrete girders developed by MnDOT and utilized for the first time on this project. The deeper girder section allowed for 154-ft-long spans, minimized the number of substructure elements, and thus reduced the impact of the bridge on the channel.

Each structure typically carries two lanes of traffic with 6-ft-wide inside and 12-ft-wide outside shoulders for a total deck width of 45 ft 4 in. The eastbound bridge widens to 65 ft 10 in. at the Minnesota abutment to accommodate on-ramp traffic from TH61 northbound. The westbound bridge widens to 66 ft 3 in. for off-ramp traffic to the adjacent rest area and park located on the Minnesota bank of the river. The segmental superstructure for each bridge was structurally optimized by using a single-cell trapezoidal box girder with deck cantilever wings. The box girder interior "core" was kept dimensionally constant everywhere to maximize casting efficiency. Variable deck width was accomplished by adjusting wing lengths and by shifting the centerline of box girder to follow the change in deck centerline where width demanded. The prestressed concrete beam spans feature four girders per bridge spaced at 12 ft centers.

Bridge drainage requirements were kept to a minimum by careful design of the roadway longitudinal and transverse deck profile. A drainage conveyance system was designed by MnDOT for remaining flows to carry drainage to detention ponds on each end of the bridge. Pipes were kept to the inside of each bridge as much as possible to hide them from view, and were designed with extra capacity for potential winter freezing, higher than design-level flows, and unexpected blockages.



April 2015 view of the main channel of the Mississippi River looking downstream from the Minnesota bank. The segmental concrete solution built from above allowed uninterrupted commercial and recreational use of the river during construction.

Segmental Solution

MnDOT selects segmental concrete bridges for their many initial and long-term benefits. A concrete segmental bridge for the new I-90 crossing near Dresbach is a sustainable solution for successfully addressing all project constraints, criteria, and goals. The use of concrete spurs the local economy through the utilization of local labor, materials, and resources. Building from above in balanced cantilever minimizes construction impacts, while efficient, cost-effective long spans result in the least-practical permanent bridge footprint for the best environmental stewardship.

The concrete segmental solution provides a highly redundant, low maintenance, and resilient structure with bidirectional pre-compression of the entire concrete superstructure, enhancing the long life of the bridge. Integral wearing surfaces cast with the section are also pre-compressed, resulting in a riding surface highly resistant to deicing chemicals. The likelihood of ever having to replace this surface over the long service life of the segmental bridge is very low. MnDOT is also at the forefront of the use of

MINNESOTA DEPARTMENT OF TRANSPORTATION, OWNER

OTHER CONSULTANTS: Geotechnical Engineering, American Engineering Testing, St. Paul, Minn.; Independent Construction Cost Estimating, Armeni Consulting Services, Suwanee, Ga.; Electrical Engineering, Cain Thomas Associates, White Bear Lake, Minn.; Bridge Aesthetic Lighting, Randy Burkett Lighting Design, St. Louis, Mo.; Construction Inspection and Segmental Geometry Control, Figg Bridge Inspection, Apple Valley, Minn.; and Contractor's Construction Engineer, FINLEY, Tallahassee, Fla.

OTHER MATERIAL SUPPLIERS: Form Travelers, Schwager Davis Inc., San Jose, Calif.; Formwork, EFCO, Des Moines, Iowa; Reinforcing Steel Fabricator, CMC Rebar, Kankakee, Ill.; and Bearings and Expansion Joints, The D.S. Brown Company, North Baltimore, Ohio

BRIDGE DESCRIPTION: Twin, 2593-ft-long structures, each featuring a four-span, 1667-ft-long, cast-in-place, post-tensioned, segmental box-girder unit built from above in balanced cantilever over the main channel, and a six-span, 926-ft-long precast, pretensioned concrete beam unit over the east channel. Segmental spans are 323, 508, 508, and 328 ft, and beam spans are typically 154 ft with a 156-ft end span.

stainless steel reinforcement in bridge decks, providing another layer of deck protection for all of the Dresbach spans. These specified details for the bridge directly benefit MnDOT by significantly reducing life-cycle costs associated with maintenance operations common to other structure types.

High-performance concrete ensures strength and long-term performance. Concrete mixtures featured compressive strengths up to 8 ksi, fly-ash and slag cement, and criteria for alkali-silica reaction (ASR), scaling resistance, shrinkage, permeability (less than 1500 coulombs), visual ratings, and fine/coarse aggregate expansion.

The deck for the prestressed beam spans also includes high-performance concrete, stainless steel reinforcement, and an integral wearing surface for enhanced life.

Context-Sensitive Design

The segmental bridge offered the greatest opportunity for aesthetics, which was important to the local communities and stakeholder group. Aesthetic design inspiration for the Dresbach Bridge comes from the picturesque natural landscape of the surrounding area. Functional requirements of the crossing are enhanced through context-sensitive design developed with an understanding of the prominence, use, and visual features of the Mississippi River and nearby heavily forested bluffs and islands.

The portion of the bridge crossing the main channel requires functionality and contextual aesthetics both within the environment and at a pedestrian level. This portion of the bridge is the most visible from the surrounding areas including many viewpoints along the Minnesota bank, and from commercial river traffic.

After passing over the main channel, the bridge crosses an island covered with old growth trees. This east channel portion of the structure is contextually dominated by the river-level experience of recreational users.

Pier Shape

Perhaps the greatest aesthetic opportunity came in custom shaping the main and east channel bridge piers. The heavily forested surroundings feature old-growth trees that appear to emerge from the water with great size and strength. Bridge piers are shaped to honor the feel of the trees and extend the forest environment across the river. While providing the strength to support the bridge, the pier shape is that of the trunk of a majestic tree supporting its foliage above. The complex three-dimensional layering and tapering of the piers, their extension up and along the outside of the superstructure, and the openings between them reflect the organic nature of a tree that's grown unconstrained in its native surroundings.

Traffic is switched to the new eastbound bridge in November 2015 with completion of the new westbound bridge scheduled for June 2016.

October 2015 view of the main river piers with the high Minnesota bluff beyond. Main channel piers are shaped to honor old-growth trees prevalent in the heavily forested surrounding landscape.

In the main channel, the structural and functional pier pedestals also provide a strong visual base element in the same way that the lower portion of a trunk supports the tree. The shaping of these supporting pedestals carefully considered the forest inspiration in addition to being streamlined for river flow and ice considerations. The complex piers were designed to keep the shape and structural core constant at all locations for schedule, labor, and cost savings.

All reinforcing steel details, bends, and tolerances were provided in the contract plans, eliminating the need for shop drawings. Cages were pre-assembled on the ground and lifted into position. Pier construction progressed seamlessly with outstanding results.

Color

Color selection for the river bridge played a key role in ensuring that the structure would fit with and complement the surrounding environment. In addition to the river and forested environment, the context also includes a high bluff on the Minnesota side. The presence, and often dominance, of a unique light and golden tan palette on the bluff became the driving factor in the community's selection of a rich tan color for the bridge.

Abutment and Retaining Wall Treatments

The Minnesota and Wisconsin abutments and connecting roadway

approaches contain multi-tiered retaining walls with variable treatments for overall project aesthetic compatibility. Stone texturing, sand-blasting, and smooth areas that are single and multi-colored tie the river bridges to the new interchange with consideration of the river, forest, and bluff environments.

Construction

MnDOT awarded the project in early 2013 for a river bridge low bid of $81.5 million. A competitive bidding environment resulted in a 15% project savings for MnDOT compared to pre-bid, independent contractor-based estimates.

Construction began in the spring of 2013 focused on the installation of cofferdams, piling, and seal slabs for the main span piers flanking the river navigational channel. Eighty-foot-tall cofferdams facilitated footing construction below the river mudline in accordance with MnDOT design standards. Pedestals through the water depth (including flood levels) resist barge impact and significant ice loading while being oriented within the flow to minimize drag and scour potential.

Despite spring flooding and difficult Minnesota winter conditions within the first 12 months, significant progress was made including the construction of all nine eastbound bridge piers plus seven of the nine westbound piers. This included four of the six twin-wall main river piers constructed in the tree shape. A cold-weather concreting plan following MnDOT requirements allowed construction to continue throughout the winter. This included thermal analysis, insulation techniques, and continuous monitoring. Construction of the pier footings and pedestals included mass concrete provisions to control the heat of hydration, keeping core and differential temperatures within specified limits. Concrete mixtures with slag cement and a cooling tube system were also used.

Segmental superstructure construction began with the first segment cast on May 21, 2014, located at the eastbound pier table 3. Superstructure casting utilized two pairs of form travelers launched from two adjacent piers operating at the same time for schedule savings. A typical segment production rate of four segments per week was achieved for the first three cantilevers comprising the eastbound bridge. This was increased to a peak rate of six segments per week after moving travelers to the westbound bridge to complete the segmental spans.

The east channel girder spans were erected simultaneously, saving significant time and the schedule. A combination of temporary steel trestles and stone causeways were constructed within the east channel to allow for delivery and erection of the girders while meeting environmental requirements for water passage. A temporary trestle lift-span allowed recreational river users to cross through the construction zone. Girders were shipped to the construction site over interstate and state highways, and were loaded onto the temporary trestle/causeway near the Wisconsin abutment. No special permitting was required for the larger girders since axle loads were kept within limits. Transverse trestle and causeway "fingers" provided work platforms necessary for the movement and staging of cranes for girder placement on the east channel piers.

Milestones in 2015 included the completion and opening of the eastbound bridge in early November, in time for increased holiday traffic volumes. Cantilever 3 for the westbound bridge and all of the east-channel beam spans were also completed. An unusually mild fall and winter that continued into early 2016 enabled acceleration of the westbound bridge construction.

Current Project Status

The Dresbach Bridge is on track for early completion thanks to accelerated segmental bridge construction and good weather. Superstructure work is complete with only barriers, joint installation, and final riding surface texturing remaining. The dual bridges were scheduled to be fully open to traffic in June 2016, several months ahead of schedule.

Traffic has been removed from the existing bridge and demolition activities are underway. The deck is being removed by jack-hammering with debris falling into collection barges stationed on the river below. Cranes on barges will remove the steel girders, followed by demolition of the piers to water level. Portions of the piers below water will be removed by underwater blasting, with debris removed from the river bottom with clam-shell buckets to the satisfaction of the U.S. Coast Guard and Corps of Engineers. Bridge demolition is scheduled for completion in the fall of 2016.

October 2014 view of the eastbound segmental cantilever construction of pier 2 over the main river channel. Superstructure casting progressed quickly achieving a typical rate of four segments per week and a peak rate of six segments per week.

Eric Breitsprecher is engineering specialist in charge of Dresbach Bridge construction for the Minnesota Department of Transportation District 6 in Rochester. Courtney C. Oltman is a bridge engineer, Stephen E. Fultz is regional director and project manager, and John R. Dvorak is a senior bridge engineer, of FIGG's Western Regional Office in Englewood, Colo.

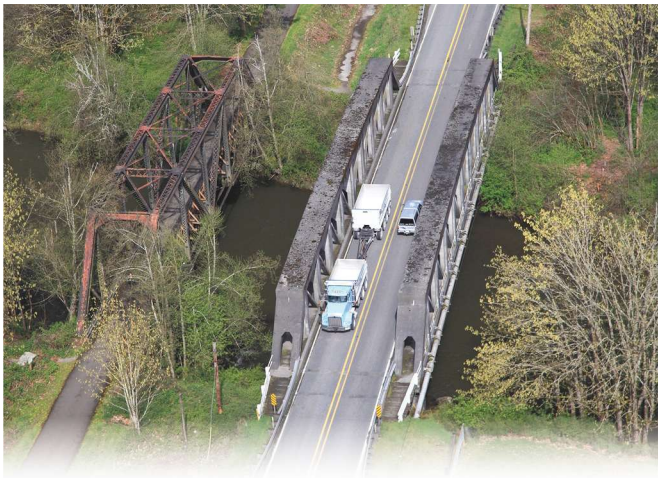
EDITOR'S NOTE

The final concrete closure placement took place in April 2016 for the new Dresbach Bridge linking the U.S. states of Minnesota and Wisconsin across the Mississippi River.

State Route 162/6 Puyallup River Bridge

Successful bridge replacement in Washington State using prestressed, lightweight concrete girder superstructure

by David Chapman, Concrete Technology Corporation, and Eric Schultz and Bijan Khaleghi, Washington State Department of Transportation



State Route 162/6 existing historical concrete pony truss bridge that was replaced. Photo: Washington State Department of Transportation.

State Route 162 is a two-lane highway that services several rural towns in western Washington. This short section of highway, only 17.5 miles in length, contains 10 separate water crossings. One of these crossings is over the Puyallup River near the town of Orting. A uniquely designed concrete truss bridge had been in service over the river for some 81 years. This historical, existing bridge had reached its functional limitation, which required that a replacement structure be built: the State Route 162/6 Puyallup River Bridge.

The New Bridge

A new roadway alignment was designed to allow the replacement bridge to be constructed adjacent to the existing bridge. This made it possible to maintain traffic during construction. The new alignment required a 3300-ft radius horizontal curve throughout most of the length of the bridge. The replacement bridge contains two spans of prestressed, lightweight concrete girders with a 7.5-in.-thick, cast-in-place, reinforced normal-weight concrete bridge deck supporting concrete traffic barriers at each side. The two spans are 110 and 160 ft for an overall length of 270 ft. A nonsymmetrical span arrangement was chosen to allow the center pier to be constructed out of the river, on the bank, while maintaining an opening large enough to meet the hydraulic requirements of the river. The 40-ft curb-to-curb width allows for two, 11-ft-wide lanes and two 9-ft-wide shoulders.

Prestressed lightweight concrete girders were used for the new bridge. Photo: Washington State Department of Transportation.

Girder Selection

The initial girder choice was to utilize the Washington State Department of Transportation (WSDOT) WF74G girder type, which is a 74-in.-deep girder with a 49-in.-wide top flange. The WSDOT bridge and structures office was looking for a suitable structure to evaluate the use of prestressed, lightweight concrete girders and selected this bridge due to its limited size and medium-length spans. The use of prestressed, lightweight concrete girders had been contemplated in the past, but concerns about girder properties—specifically the modulus of elasticity, creep, and shrinkage values—deterred WSDOT from using them.

Advantages

Weight reductions as a result of using lightweight concrete for the production of girders generally helps reduce substructure sizes. For instance, the depth to which shafts require embedment is controlled by either vertical or lateral loads. The vertical loads are reduced in two ways. The most obvious way is from the reduced girder weights. However, reduced girder weights can also reduce the size of pier crossbeams, which further reduces the dead load. These combined reductions lead to a smaller mass in the superstructure, which can reduce the seismic lateral loads to the foundations. These smaller foundation elements lead to cost savings in construction of the bridge.

Reduced girder weight for a given span length also has the advantage of requiring smaller crane and hauling

profile

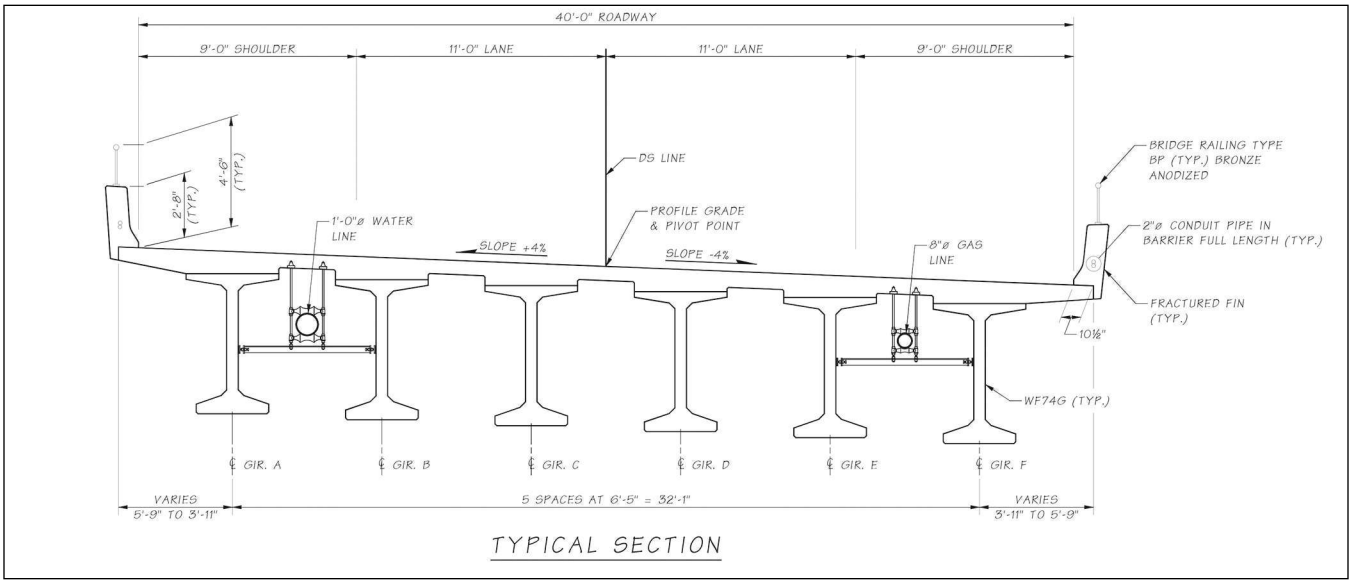
STATE ROUTE 162/6 PUYALLUP RIVER BRIDGE / PIERCE COUNTY, WASHINGTON

BRIDGE DESIGN ENGINEER: Washington State Department of Transportation, Tumwater, Wash.

PRIME CONTRACTOR: Selby Bridge Company Inc., Vancouver, Wash.

PRECASTER: Concrete Technology Corporation, Tacoma, Wash.—a PCI-certified producer

LIGHTWEIGHT AGGREGATE SUPPLIER: Carolina Stalite Company, Salisbury, N.C.



Typical section of the superstructure of the State Route 162/6 Puyallup River Bridge with Washington State Department of Transportation WF74G girder type. Figure: Washington State Department of Transportation.

equipment when compared with normal-weight concrete girders.

For this structure, a weight savings for the entire superstructure was achieved by using the lightweight girders instead of normal-weight girders. This total reduction in dead load was about 300 kips, with half of this reduction being realized at the single column/shaft at pier 2.

Contract Requirements

The contract documents limited the unit weight of the concrete in the girders (when fresh, and not including reinforcement) to 125 lb/ft^3. There was also a limitation placed on the absorption of the coarse aggregate, which was required to be less than 10% when tested in accordance with the American Association of State Highway and Transportation Officials' (AASHTO's) AASHTO T 85, *Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate*. In addition, the coarse aggregate gradation was required to conform to AASHTO M 195, *Standard Specification for Lightweight Aggregates for Structural Concrete*.

Properties

The specified concrete compressive strengths at prestress tranfer and at 28 days were 7.5 and 9.0 ksi, respectively. During the design phase of a project, it is important to be able to predict creep and shrinkage values with some level of accuracy. Too much variation in these values can lead to issues in the construction and final profile of a bridge roadway. For prestressed concrete girder bridges, WSDOT's method of design and resulting constraints on the construction sequence positions the girders vertically far enough below the bottom of the bridge deck to eliminate interference from the top flange of the girder as camber grows prior to construction of the deck. The gap between the top flange of the girder and the bottom of the bridge deck is filled with concrete as part of the bridge deck concrete placement.

If the camber growth of the girder is too large, then the top of the girder can intrude into the bottom reinforcement in the bridge deck. And if the camber growth is too small or negative, then the gap between the top of the girder and the bottom of the deck will create a large added dead load to the bridge.

Determining a reliable unit weight and modulus of elasticity are necessary to calculate creep and shrinkage coefficients that provide reasonable camber estimates. The modulus of elasticity used for the design of the State Route 162/6 Puyallup River Bridge was computed using the *AASHTO LRFD Bridge Design Specifications* equation (prior to the 2015 Interim Revisions) with the density of the sand lightweight concrete and an initial value of 1.0 for the K_1 correction factor for the source of aggregate. Testing of the sand-lightweight concrete suggested a K_1 value of 0.9 was more appropriate.

Comparisons

WSDOT designs for camber presume that the girders will be placed, and the deck cast, within a specific window of time after the girders have been fabricated. Midspan camber values are calculated for two specific elapsed times between girder fabrication and deck placement: 40 and 120 days. The calculated value at 120 days represents the upper-bound limit of the predicted camber at midspan of the girders. The lower bound is simply one half of the calculated midspan camber at 40

WASHINGTON STATE DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: A two-span, continuous-for-live-load bridge with span lengths of 110 and 160 ft, that used a cast-in-place, normal-weight reinforced concrete deck supported on prestressed lightweight concrete girders.

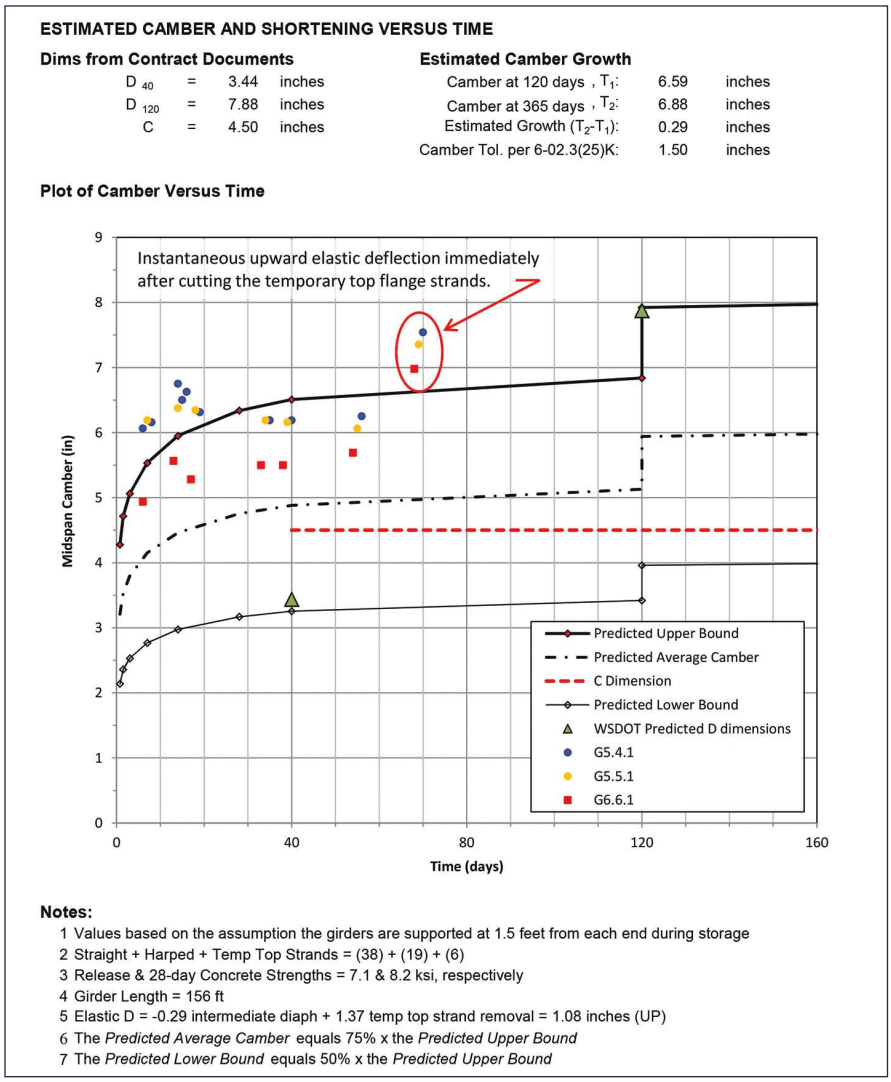
STRUCTURAL COMPONENTS: Twelve, 74-in.-deep, WF74G prestressed lightweight concrete I-girders; a 7.5-in.-thick, cast-in-place reinforced concrete bridge deck; middle pier, cast-in-place, two-stage crossbeam; and cast-in-place abutments, column, and shafts.

State Route 162/6 Puyallup River Bridge with prestressed lightweight concrete girders (Portion of span 1 and all of span 2 shown). Photo: Washington State Department of Transportation.

days. In general, the longer the span, the bigger the camber values. Span 2 is of most importance for this structure because it controls the total depth of concrete to be placed above the girder flange in order to achieve the final profile. The lower and upper camber values for the majority of the span 2 girders were given in the contract plans as 3.44 and 7.88 in., respectively.

The midspan camber of the lightweight concrete girders was measured periodically between the time of fabrication and the time of deck placement. Three of the girders in span 2 were measured at approximately 40 days after fabrication at 5.5. 6.2, and 6.2 in. These same three girders were measured again at around 55 days with values of 5.7, 6.1, and 6.3 in.

The girders were fabricated at a rate of about one girder per day and stored at the precast facility until the bridge substructure was ready to receive them. There was a difference of 8 days between the ages of the girders in span 2. They were delivered to the project when they were around 55 days old and then the temporary top strands were cut at around 70 days after fabrication.



Measured midspan camber for the State Route 162/6 Puyallup River Bridge span 2 girders D, E, and F at various times after girder fabrication. Figure: Concrete Technology Corporation.

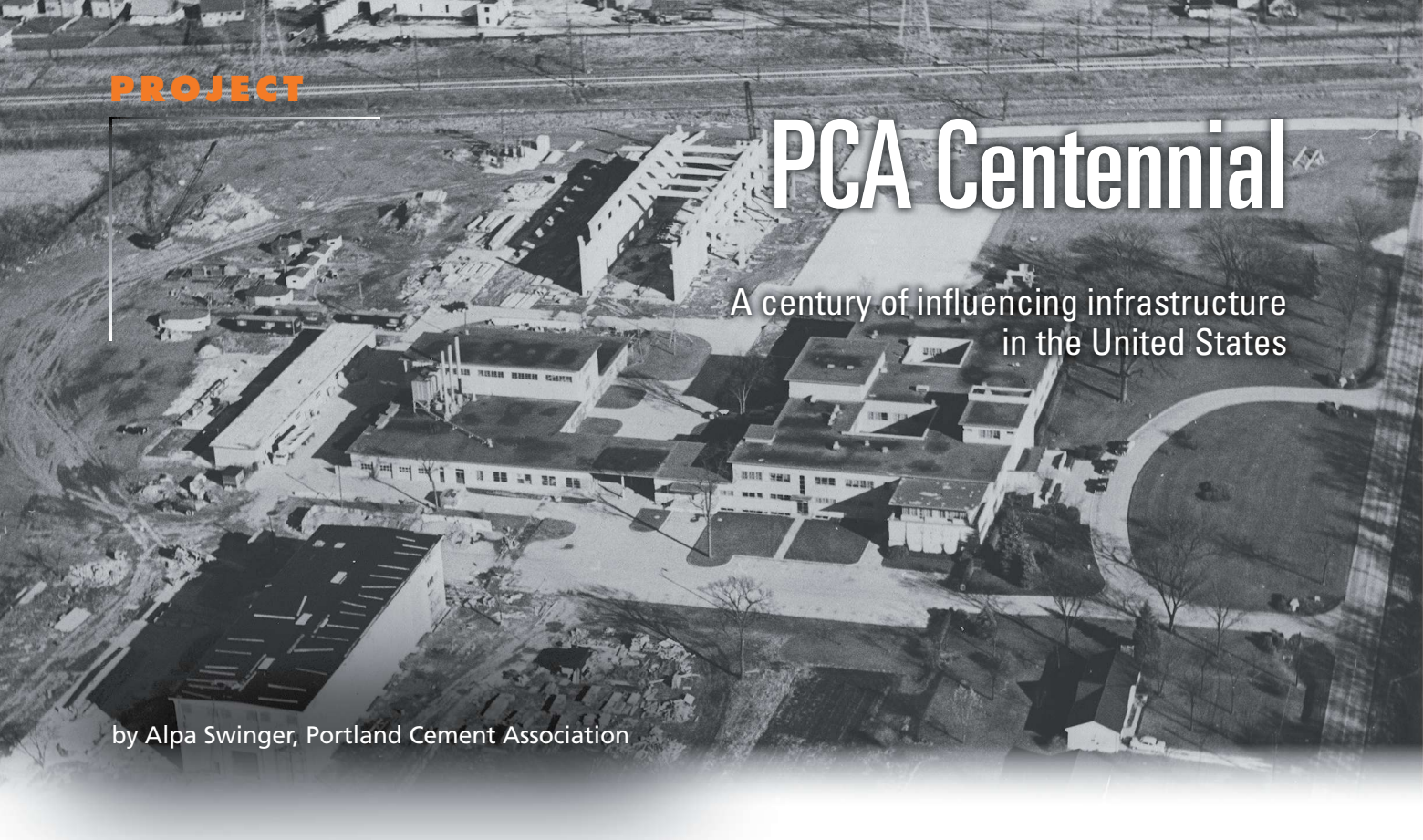
Temporary top strands were needed to prevent cracking in the top flange of the girders during shipping. This is a standard practice for medium- and long-span WSDOT girders. These temporary strands are released at the project site once the girders have been placed and the temporary bracing has been installed. The release of these strands increases the camber and the design accounts for this instantaneous growth in camber.

For the span 2 girders, the change in camber at release of the top strands was calculated to be 1.3 in. and was measured in the field to be the same. This additional camber increased the midspan cambers of the three girders to 7.0, 7.4, and 7.6 in., which was just below our calculated maximum value for the 120-day upper bound of 7.88 in. (see the figure to the left—note that calculations assumed release of top strands at a later age). The deck was cast at around 105 days after the date of girder fabrication. No camber growth was measured after the temporary top strands had been cut.

Conclusions

Use of the sand-lightweight concrete in the fabrication and construction of prestressed, lightweight concrete girders for the State Route 162/6 Puyallup River Bridge has been successful. The project demonstrated to WSDOT that it can utilize its standard design and construction methods for lightweight concrete with little to no modifications. Prestressed, lightweight concrete girder designs should follow the AASHTO LRFD specification for lightweight concrete and utilize a K_1 correction factor for source of aggregate of 0.9. (Note: Using the new equation in the AASHTO LRFD Specifications, the factor should be 1.0.) WSDOT absorption and gradation specifications should also be used to achieve predictable camber values for medium-length girders.

David Chapman is the chief engineer with the Concrete Technology Corporation in Tacoma, Wash. Eric Schultz, bridge engineer, and Bijan Khaleghi, state bridge design engineer, are with the Washington State Department of Transportation, Bridge and Structures Office in Tumwater, Wash.



PROJECT

PCA Centennial

A century of influencing infrastructure in the United States

by Alpa Swinger, Portland Cement Association

Construction at the Portland Cement Association's campus in Skokie, Ill. in the 1950s. All Photos: Portland Cement Association Archives.

The 100th Anniversary of the founding of the Portland Cement Association (PCA) provides a unique opportunity that many of us can only experience once in our lifetime. The anniversary marks an occasion to not only celebrate the association, but where the industry has come and where it is heading into the next century. This is not just a testament to the resiliency of concrete, but also its role as a building block of society. Without concrete our homes, roads, schools, and cities would not exist as they are today.

Through all of the changes in technology and society over the last 100 years, PCA's original charter still stands—like many of the concrete roads, buildings, and other structures that were built over the past century and are still in active use.

One of our original ad slogans was "Concrete for Permanence." We have modified that in this new century to discuss the importance of resiliency. Similarly to our charter, the message that we use still is just as critical as it was a century ago.

Concrete has evolved into a complex, high-tech material. However, its fundamental benefits—particularly strength, durability, and resilience—are valued today more than ever.

In 1872, David O. Saylor built the first portland cement plant in the United States, near Allentown in Pennsylvania's Lehigh Valley. Others soon followed, and by the turn of the twentieth century, cement was emerging as a construction staple.

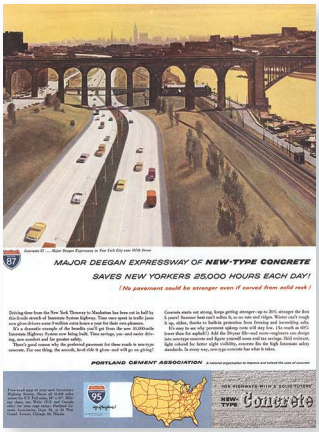
This increasing popularity brought about a serious problem. At that time cement was sold in cloth sacks. Buyers paid a deposit on each sack, which was refunded upon return of the sack to the plant for re-use. But return of sacks for refilling was slow and erratic, and they were often in poor condition. Sacks were often stolen from construction sites and cashed in for deposits. Railroads complained of poor packaging and labeling.

B.F. Stradley of Vulcanite Portland Cement Company wrote to cement company executives calling for a meeting to discuss "the present methods of handling sacks, which are almost universally unsatisfactory" and proposed that an industry group be formed to facilitate the collection, repair, and recycling of cement sacks. Accordingly, in 1902 cement makers formed the Association of American Portland Cement Manufacturers (AAPCM).

As the industry continued to expand, there were needs for reliable technical information, research, and uniform test methods and standards. In 1916, the AAPCM was reorganized as the Portland Cement Association to address these needs.

PCA began operations with 53 cement company members, a headquarters office in Chicago, eight district offices, and a total of 121 employees. Promotion and government affairs were priorities right from the start. The year of PCA's founding was also the year that the U.S. Congress passed the first federal-aid highway act, setting into motion a network of national highways.

PCA marketed concrete roads aggressively with an advertising campaign in 10 national weeklies, 23 trade magazines, and 59 farm journals. These early ads stressed the value of paved roads for the distribution of food and other products, including the idea that



Various advertisements that were placed in national weeklies, trade magazines, and farm journals as part of the Portland Cement Association's marketing campaign in the 1950s.

concrete roads provided better fuel economy.

In 1956, the Federal Aid Highway Act ushered in the age of the interstate. PCA launched an ad campaign that took the benefits of "New-Type Concrete" directly to consumers with a parade of celebrity pitchmen. Bob Hope, Robert Young, Art Linkletter, Sam Snead. . .the list read like a late-1950s who's-who of actors, sports figures, and television personalities who trumpeted "new type" concrete for the "Sweetest Ride Yet."

Beyond its importance for transportation and economic development, the interstate highway system became an integral part of American life and culture because of the mobility it fostered.

Housing emerged as priority as well. Appearing in *Time* magazine and other leading publications of the day, PCA consumer ads in the 1930s and beyond targeted single-family housing. Messages were built around benefits such as fire safety, security, and durability.

In the 1960s, PCA teamed up with several allied industry groups to jointly sponsor the Concrete Industries Horizon Homes program in cooperation with the National Association of Home Builders. Each year one national award and seven regional awards were given to builders whose entries showed the best merchandising and design efforts. The top national award prize was a trip for two to any destination in the world.

Throughout the decades, PCA's market development has been based on solid research and technology. Promotion messages were backed by PCA's reputation for knowledge and expertise.

In its early years PCA did everything for the concrete industry. Today's industry has evolved to a more diverse state, and

Front view of the Portland Cement Association's main building.

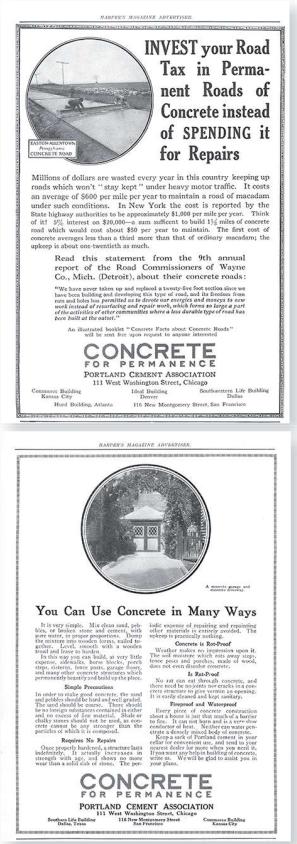
PCA has needed to provide the "glue" to bind industry segments together.

The need for cooperation and collaboration within the industry is more important today than ever. Since cement is the common denominator among all concrete applications, a natural role for PCA is to foster a unified industry effort in shared areas of interest—the same need that first drew the industry together in 1916.

The PCA Centennial reminds us that over the last 100 years the cement industry has made possible a building material that has been essential to the development of this nation. Indeed, concrete is vital to civilization itself.

Alpa Swinger is the director of infrastructure marketing for the Portland Cement Association in Skokie, Ill.

Overhead view of the Portland Cement Association's campus in Skokie, Ill.



HARPER'S MAGAZINE ADVERTISER.

INVEST your Road Tax in Permanent Roads of Concrete instead of SPENDING it for Repairs

EASTON-ALLENTOWN ROAD, Near Bethlehem, Pa. CONCRETE ROAD

Millions of dollars are wasted every year in this country keeping up roads which won't "stay kept" under heavy motor traffic. It costs an average of $600 per mile per year to maintain a road of macadam under such conditions. In New York the cost is reported by the State highway authorities to be approximately $1,800 per mile per year. Think of it! 5% interest on $20,000—a sum sufficent to build 1½ miles of concrete road which would cost about $50 per year to maintain. The first cost of concrete averages less than a third more than that of ordinary macadam; the upkeep is about one-twentieth as much.

Read this statement from the 9th annual report of the Road Commissioners of Wayne Co., Mich. (Detroit), about their concrete roads:

"We have never taken up and replaced a twenty-five foot section since we built the first concrete road in 1909. Our roads have been subjected to heavy traffic and have not permitted us to devote our energies and moneys to new work instead of resurfacing and repair work, which forms as large a part of the activities of other communities where a less durable type of road has been built at the outset."

An illustrated booklet "Concrete Facts about Concrete Roads" will be sent free upon request to anyone interested

CONCRETE FOR PERMANENCE

PORTLAND CEMENT ASSOCIATION

111 West Washington Street, Chicago

Commerce Building, Kansas City · Ideal Building, Denver · Southwestern Life Building, Dallas · Hurd Building, Atlanta · 116 New Montgomery Street, San Francisco

HARPER'S MAGAZINE ADVERTISER.

A masonry garage and summer dressing

You Can Use Concrete in Many Ways

It is very simple. Mix clean sand, pebbles, and Portland cement with pure water, in proper proportions. Pour the mixture into wooden forms, nailed together with ordinary tools, with a wooden tool and trowel to finish.

In this way you can build, at very little expense, sidewalks, horse blocks, porch steps, cisterns, fence posts, garage floors, garage walls, and many other things which permanently beautify and hold up the place.

Simple Precautions

In order to make good concrete, the sand and pebbles should be clean and well graded. The sand should be coarse. There should be no foreign substances contained in either the sand or the pebbles. Soft, dirty, chalky stones should not be used, as concrete cannot be any stronger than the particles of which it is composed.

Requires No Repairs

Once properly hardened, a structure lasts indefinitely. It actually increases in strength with age, and shows no more wear than a solid rock or stone. The periodic expense of repairing and repainting other materials is thus avoided. The scheme is practically nothing.

Concrete is Rot-Proof

Weather makes no impression upon it. The soil moisture which rots away stags, fence posts and porches, made of wood, does not even disfigure concrete.

Is Rat-Proof

No rat can eat through concrete, and the rat will not gnaw a hole in a concrete structure to give vermin an opening. It is easily cleaned and kept sanitary.

Fireproof and Waterproof

Every piece of concrete construction is fireproof. It will not burn, nor will it melt in fire. It can not burn and is a non-conductor of heat. Neither can water penetrate a densely mixed body of concrete.

Keep a sack of Portland cement in your cellar, garage, or barn. Use it when you need it. If you want any help in building of concrete, write us. We will be glad to assist you in your plans.

CONCRETE FOR PERMANENCE

PORTLAND CEMENT ASSOCIATION

111 West Washington Street, Chicago

Southern Life Building, Dallas, Texas · 116 New Montgomery Street, San Francisco · Commerce Building, Kansas City

Advertisements touting the permanence of concrete.

Assure Quality! Specify PCI Certification!

PCI certification is the industry's most proven, comprehensive, trusted, and specified certification program. PCI certification offers a complete regimen that covers personnel, plant, and field operations. This assures owners, specifiers, and designers that precast concrete products are manufactured by companies that subscribe to nationally accepted standards and that are audited to ensure compliance.

PCI certification is more than just inspections and documentation. It is based on, and integrated with the precast concrete industry's Body of Knowledge. For over 60 years, PCI has set the standards and developed, maintained and disseminated the body of knowledge for the design and construction of precast concrete structures. This feat is set on the foundation of millions of dollars of research, dozens of technical guides and manuals, a network of over 70 committees, PCI's professional and experienced staff, and support of over 2000 PCI members.

PCI CERTIFICATION™

To learn more about PCI certification and PCI, go to: www.pci.org/certification

Or call
Dean Frank, P.E.
Director, Quality & Sustainability Programs
Precast/Prestressed Concrete Institute
200 W. Adams Street, Suite 2100
Chicago, IL 60606
312-786-0300

150 Years of DYWIDAG-SYSTEMS INTERNATIONAL

by Dave Martin, DYWIDAG-Systems International USA Inc.

Bruecke-aus-Stampfbeton made of high-compression concrete.

DYWIDAG is celebrating a special anniversary: 150 years. At this time, we are looking back at the beginnings of modern industrial construction and reflecting on the extraordinary achievements of DYWIDAG engineers. These achievements continue to motivate us to develop creative and technically innovative solutions for construction. Now, in the twenty-first century, more and more daring architectural designs are possible, and we know that this creative power would have been unthinkable had it not been for the development of new concrete construction methods, from precast concrete to post-tensioning.

It is difficult to appreciate today how much technical knowledge and risk-taking was needed to begin using unreinforced concrete. This original concrete was compacted by pressure surges during pounding (compressed concrete) in structures for which safety had to be of the utmost importance.

1880—12-m (39 ft) Span in Dusseldorf

One of the first concrete bridges in Germany using this technology was built by DYWIDAG in 1880. It was an exhibition bridge with a 12-m (39 ft) span that carried a pavilion and stood on the premises of Dusseldorf's trade and art exhibition. The demolition of the bridge at a later stage was extremely difficult due to the high compression of the concrete. For a quarter century thereafter, DYWIDAG built compressed concrete bridges.

In 1922, DYWIDAG built a unique, 60-mm-thick (2.4 in.), 25-m-diameter (82 ft) dome structure. Still today, the construction material concrete is constantly proving its superiority around the world for shell construction and in post-tensioning. Both construction methods are inseparably connected with the name of Dyckerhoff & Widmann AG (DYWIDAG).

1927—Saale Bridge Alsleben

In 1927, DYWIDAG was awarded the contract for construction of the Saale Bridge Alsleben, having designed an innovative dual pivot arch rib structure with stress ribbons. During construction, the stress ribbons were first connected with one side of the 68-m-long (223 ft) arches and loosely positioned above a recess in the middle of the longitudinal girders for the bridge deck. Afterwards, the stress ribbons were tensioned using a newly developed puller until they had reached their working load and were then concreted. This project represented the first important step towards post-tensioned concrete.

The post-tensioning construction method developed by DYWIDAG introduced an innovative period for the construction industry. Thanks to this method, it may be said that concrete triumphed over the laws of gravity and it was used in new areas for the first time. Even major bridges could be built using post-tensioning and concrete instead of the steel construction method.

1965—Pioneer Work and a World Record

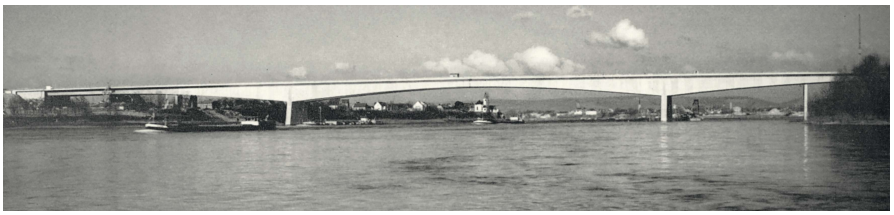
A convincing example for this development is the Bendorf Bridge, which crosses the Rhine north of Koblenz, Germany. With a span of 208 m (682 ft), it was the world's widest concrete girder bridge when opened in 1965. Even today, it is still fully functional.

Know-How for International Projects

In the 1950s, in addition to its traditional business area of construction, DYWIDAG began signing license and consulting contracts for the application of the different DYWIDAG construction methods around the world. The success in post-tensioning was especially helpful for DYWIDAG in this process. This mainly applied to the following areas:

- Bridges built using the DYWIDAG Post-Tensioning System
- Construction of large bridges using the patented DYWIDAG Free Cantilever Method
- DYWIDAG Prestressed Concrete Sleepers (Crossties)

In Europe, the DYWIDAG Post-Tensioning System was mainly used in conjunction with the free cantilever method and the use of precast concrete elements. The first projects were the Freudenau Harbor Bridge and the Au-Leistenau Bridge in Austria. In Sweden, a large number of bridges were built using the free cantilever and precast concrete methods. Examples include the bridge leading over the Kallosund near Skagerrak with a main span of 94 m (308 ft), which was completed in 1957. Additional license agreements were signed in Denmark, Finland, Norway, and the Netherlands.



Bendorf Bridge near Koblenz, Germany, was the world's widest concrete girder bridge when it opened in 1965.

Kap Shui Mun Bridge in Hong Kong, China, is an example of DSI Cable-Stay Technology.

Abraham Lincoln Bridge, Louisville, Ky. is an example of a DSI International Partnership.

Beginnings of DYWIDAG-Systems International

The license and consulting business was a completely new business idea for a conventional construction company. DYWIDAG had already begun to successively sign license and consulting contracts for the application of the DYWIDAG construction methods in many countries in the 1950s. The continuous extension of the license business formed a successful part of DYWIDAG's international business.

The positive results in the license business also caused DYWIDAG to venture into the United States and Canada. Consequently, DYWIDAG Inc. was founded in the USA in 1969, and a representative office was also opened in Canada.

In the following years, the geotechnical product range was increasingly expanded, and at the same time, the Strand and Bar Post-Tensioning System portfolio was continuously widened in accordance with the dynamic market development. Sales were carried out both via the international network of licensees and via affiliated companies. The DYWIDAG THREADBAR™ was revolutionary for civil applications, and DYWIDAG's research and development department worked on the development of additional high-quality geotechnical systems at full speed.

1979—Foundation of DYWIDAG-Systems International

Thus, the DYWIDAG license department became the independent company DYWIDAG-Systems International (DSI) in 1979. The new DSI changed very quickly and increasingly acted as a global company. At the beginning of 1979, DSI already had more than 450 employees.

DSI continuously strengthened its international business, and the products and systems were further adapted and optimized to suit the requirements and needs of local markets. The two pillar model consisting of DYWIDAG Post-Tensioning Systems and DYWIDAG Geotechnical Systems was continuously developed over the course of time, and the know-how in post-tensioning was used to develop additional systems with different anchorage types for cable-stayed bridges. A unique example for this special know-how was the construction of the Kap Shui Mun Bridge in Hong Kong, China, in 1995.

2000—Market Entry into Mining

In September 2000, the company entered the specialized ground support market through acquisitions in Australia and later plants were established in South Africa and North America in 2002.

2016—Today

The DSI network is stronger than ever and our success is based on a clear strategy. In construction, we are successful in the business segments of Post-Tensioning, Geotechnics, and Structural Repair and Strengthening. In underground, we are active in the business segments Mining and Tunneling. Today, approximately 2300 dedicated employees around the world work for the DSI Group.

We uphold the awareness and the values derived from our 150-year-long history—this is what we stand for—each and every one of our experienced and dedicated staff members. We are continuously developing new and innovative systems for exciting and challenging construction projects around the globe and continue to operate with a **Local Presence and Global Competence**.

For More Information

- dsiamerica@dsiamerica.com
- dsiamerica.com
- Bolingbrook, Illinois
  (630) 739-1100
- Structural Repair and Strengthening
  (630) 972-7513
- Mansfield, Texas
  (817) 473-6161
- Long Beach, California
  (562) 531-6161
- Tucker, Georgia
  (770) 491-3790
- Toughkenamon, Pennsylvania
  (610) 268-2221
- Pompano Beach, Florida
  (954) 532-1326

EDITOR'S NOTE

This is a special feature made available to and paid for by those companies that have brought you ASPIRE *magazine by their long-running advertising and that meet criteria established by the editors. The opinions herein do not necessarily reflect those of* ASPIRE *editors, staff, and supporting organizations.*

Use of Grade 80 Reinforcement in Oregon

by Craig Shike and Dr. Tanarat Potisuk, Oregon Department of Transportation

Chehalem Creek Bridge used for comparison of Grade 60 and Grade 80 reinforcement for 8-ft-diameter drilled shafts. All Photos and Tables: Oregon Department of Transportation.

In 2012, two local agency projects in Oregon used ASTM A706, Grade 80 steel reinforcement in large diameter drilled shafts for crossings of the Willamette River in Portland. One is the Tilikum Crossing, a cable-stayed bridge carrying a transit line and pedestrians, which is owned by the city of Portland. The other is the Sellwood Bridge, a steel deck arch, which is owned by Multnomah County.

In August of 2012, the Oregon Department of Transportation (ODOT) added guidelines for use of ASTM A706 Grade 80 steel reinforcement to their *Bridge Design and Drafting Manual* (BDDM). These guidelines were developed from discussions with an Oregon reinforcing bar manufacturer who confirmed both availability and the approximate cost premium for Grade 80 reinforcement.

ODOT is ready to move forward with expanded use of Grade 80 reinforcement.

Since those initial projects, only one additional project has used Grade 80 reinforcement. This lack of progress is primarily due to an Oregon shift in priority towards bridge repairs instead of replacements. This shift is a result of limited availability of bridge funding. However, ODOT is hopeful funding will improve in the near future. When that happens, ODOT is ready to move forward with expanded use of Grade 80 reinforcement.

Oregon anticipates increased use of ASTM A706 Grade 80 for the following reasons:

- The stress/strain curve for Grade 80 has a similar shape compared to Grade 60. This is not the case for reinforcement grades higher than 80 ksi.
- Grade 80 has an additional 33% yield strength compared to Grade 60, with only 10 to 12% additional material and fabrication cost.
- Good ductility. No. 3 thru No. 11 bars have a minimum elongation of 12%.
- Weldability.
- Reduced congestion.
- Availability.

Design with Grade 80 reinforcement uses the same processes and equations used for Grade 60 reinforcement. The American Association of State Highway and Transportation Officials (AASHTO) has confirmed this and raised the permitted yield strength from 75 to 100 ksi in the *2013 Interim Revisions of the AASHTO LRFD Bridge Design Specifications*.

Availability of Grade 80 reinforcement is improving due to increased use of Grade 80 reinforcement in the building industry. At this time, a minimum order of 50 tons for each size and cut length is recommended by rolling mills in the Oregon market. This minimum order size is mentioned several times in the following discussion, but will likely differ for each rolling mill and local market.

The following applications are good opportunities to use Grade 80 reinforcement:

- Drilled shafts: both longitudinal and lateral reinforcement
- Bridge decks: especially if design can be limited to a single bar size

- Crossbeams: for main flexural steel, use same bar size top and bottom

Oregon does not recommend using Grade 80 reinforcement in columns or other members that require the ability to form a plastic hinge under seismic loading. Research is ongoing to support use of Grade 80 reinforcement in these applications, but is not complete at this time. Early research results are promising.

Design Examples

Use of Grade 80 reinforcement will reduce steel quantity and cost. Three examples are presented to illustrate the potential cost savings:

- Drilled shaft: 8-ft-diameter by 100-ft-long drilled shaft with Grade 80 reinforcement for both longitudinal bars and lateral spiral bars
- Bridge deck: 82 ft by 277 ft bridge deck (22,800 ft^2)
- Concrete crossbeam: Two concrete crossbeams, 6 ft wide by 10 ft deep by 68 ft long

All three examples accounted for the increased splice lengths associated with Grade 80 reinforcement. All examples used $0.90 per pound for Grade 60 reinforcement and $0.95 per pound for Grade 80 reinforcement. Note that the 10% to 12% cost premium for Grade 80 reinforcement need only be applied to rolling cost, not the fabrication and installation cost. In many cases the fabrication and installation costs are also reduced because there are fewer bars to place and tie.

The Indian Creek Bridge used for comparison of Grade 60 and Grade 80 reinforcement for the reinforced concrete crossbeams.

Jackson School Road over Highway 47 Bridge used for comparison of Grade 60 and Grade 80 reinforcement for the reinforced concrete deck.

Table 1. Comparison of the designs of 8-ft-diameter drilled shafts for the Chehalem Creek Bridge with Grade 60 reinforcement and Grade 80 reinforcement.

Reinforcement Grade	Grade 80	Grade 60
Longitudinal bars	Twenty-eight, No. 11, three-bar bundles (53,800 lb)	Thirty-six, No. 11, three-bar bundles (66,200 lb)
Transverse bars	No. 6 spiral at 4 to 8 in. spacing (8100 lb)	No. 6 spiral at 3 to 6 in. spacing (10,600 lb)
Total bar weight	61,900 lb (19% less)	76,800 lb
Cost	$58,800 (15% reduction)	$69,100

Drilled Shafts

Drilled shafts are desirable candidates for Grade 80 reinforcement because they are known for having congested reinforcement and requiring only two bar sizes. Grade 80 bars can help alleviate congestion. Since drilled shafts are designed elastically in Oregon, seismic concerns do not prohibit use of Grade 80 reinforcement for this application.

As part of the Newberg-Dundee Bypass project in Oregon, 8-ft-diameter drilled shafts were constructed for the Chehalem Creek Bridge. These shafts averaged around 100 ft in length. Table 1 compares the design with Grade 60 reinforcement and Grade 80 reinforcement. In this comparison, the Grade 80 reinforcement option reduced the total steel weight by 19% and the steel cost by 15%. For the Chehalem Creek Bridge, the actual 2014 bid price was $0.77 per pound for Grade 80 reinforcement in the drilled shafts and $0.80 per pound for Grade 60 reinforcement used in other parts of the bridge.

For these drilled shafts, the longitudinal steel including splice lengths is around 85% of the total weight of reinforcement. Therefore, it would take two shafts of this size and length to reach the local minimum order quantity for longitudinal bars.

Bridge Deck

Deck reinforcement is another logical location to consider using Grade 80 reinforcement. When Grade 80 reinforcement is used in a deck, it is usually possible to limit the bar size to a No. 4 bar. If so, longitudinal and transverse bars can both use the No. 4 size. When No. 4 bars are used in both directions, it is easier to meet the minimum order quantity.

Table 2 compares Grade 60 reinforcement with Grade 80 reinforcement for an overcrossing structure with a width of 82 ft and a length of 277 ft (22,800 ft^2). The design with Grade 80 reinforcement reduced the steel weight by 16% and the cost of the deck steel by 11% (around $13,000). With the smaller bar size, the Grade-80 reinforcement design had tighter spacing of the main flexural bars, which improves the performance against crack control. Note that this deck was large enough to reach the 50-ton minimum quantity.

Table 2. Comparison of the designs of the reinforced concrete deck for the Jackson School Road over Highway 47 Bridge with Grade 60 reinforcement and Grade 80 reinforcement.

Reinforcement Grade	Grade 80	Grade 60
Transverse bars	No. 4 at 6.5 in. spacing in prestressed concrete girders No. 4 at 6 in. spacing in cast-in-place concrete box girders	No. 5 at 7.5 in. spacing in prestressed concrete girders No. 5 at 7.5 in. spacing in cast-in-place concrete box girders
Total bar weight	110,800 lb (16% less)	131,300 lb
Cost	$105,300 (11% reduction)	$118,200

Table 3. Comparison of the designs of the reinforced concrete crossbeams for the Indian Creek Bridge with Grade 60 reinforcement and Grade 80 reinforcement.

Reinforcement Grade	Grade 80	Grade 60
Longitudinal bars	Nine, No. 11 bars top row Twelve, No. 11 bars bottom row 2 Eighteen, No. 11 bars bottom row 1 (31,350 lb)	Twelve, No. 11 bars top row Twenty, No. 11 bars bottom row 2 Twenty, No. 11 bars bottom row 1 (38,950 lb)
Transverse bars including temperature reinforcement	No. 6 stirrups at 8 in. (19,800 lb)	No. 6 stirrups at 6 in. (22,300 lb)
Total bar weight	51,150 lb (16% less)	61,250 lb
Cost	$48,600 (12% reduction)	$55,100

Concrete Crossbeam

Concrete crossbeams often have high levels of reinforcement congestion. Use of Grade 80 reinforcement will certainly reduce congestion. Meeting crack control requirements may reduce some of the effectiveness of Grade 80 reinforcement. The example shown in Table 3 is for two 6-ft-wide by 10-ft-deep by 68-ft-long crossbeams for Indian Creek Bridge in Eastern Oregon. For this example, both flexural bars and stirrups were assumed to use Grade 80 reinforcement. Since the flexural bars for crossbeams were significantly larger than the skin (temperature) reinforcement, it would be reasonable to consider using Grade 80 reinforcement only for the flexural bars and keep the stirrups and skin reinforcement as Grade 60.

Conclusion

Three applications of Grade 80 reinforcement have been considered. The savings in weight from using Grade 80 instead of Grade 60 reinforcement ranged from 16 to 18% with the expected cost reduction between 11 and 15%. Some designers may be reluctant to mix Grade 60 and Grade 80 reinforcement on the same project. If this is a concern, cost savings can still be expected if Grade 80 were used for everything. If so, reduced reinforcement congestion will be an additional benefit. Members which can potentially undergo plastic hinging in a seismic event should not use Grade 80 reinforcement until research that is currently in progress can confirm whether this restriction is necessary.

Craig Shike is the bridge operations and standards managing engineer and Dr. Tanarat Potisuk is the prestressed concrete standards engineer for the Oregon Department of Transportation in Salem, Ore.

For additional photographs or information on this or other projects, visit www.aspirebridge.org and open Current Issue.

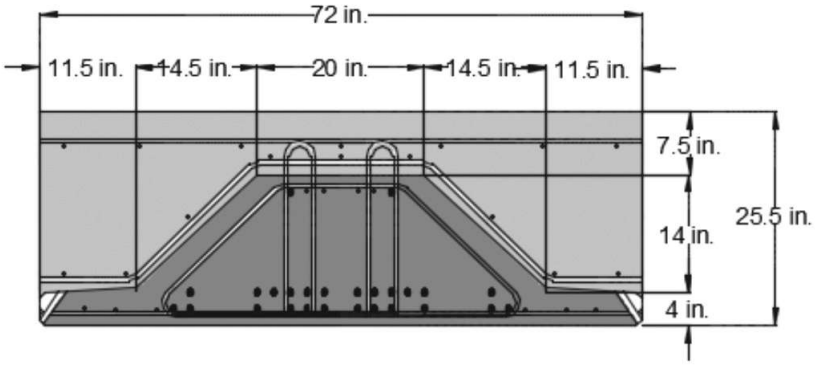
Virginia's Development of an Inverted-tee Beam Bridge Superstructure System

by Dr. Carin L. Roberts-Wollmann, Virginia Polytechnic Institute and State University, and Andrew M. Zickler and Dr. Michael C. Brown, Virginia Department of Transportation

Researchers at Virginia Polytechnic Institute and State University, with the support and cooperation of the Virginia Department of Transportation (VDOT), have developed an innovative bridge superstructure design using optimized inverted-tee prestressed concrete beams. Working with VDOT's Structure and Bridge Division and its research division at the Virginia Transportation Research Council, the team adapted a design based on concepts of the "Poutre-Dalle" section pioneered in France and variations that had been evaluated in Minnesota.

The system comprises a series of shallow prestressed concrete beams with broad shallow flanges at the bottom face that can be placed tip-to-tip as adjacent beams; a reinforced cast-in-place concrete topping is placed to unify the beams into a single slab system. The intent of the concept is to prevent development of longitudinal cracks along the joints between the adjacent prestressed concrete beams. Virginia's enhancement of this concept aimed to reduce the propensity for cracking and to increase the ease of fabrication and placement. Through interaction with fabricators and VDOT designers, the investigators arrived at a cross section that incorporates a sloped rather than a vertical web profile to decrease the concentration of stresses at the top corner of the web and to better accommodate reinforcement in the cast-in-place concrete topping. The design also eliminated horizontal reinforcement that penetrated the sides of prestressed concrete beams in previous designs. Further innovations included development of alternatives with and without welded continuous tension connections between adjacent beam flanges. The decision to use the welded connection is based on the anticipated magnitude and frequency of truck loading on the bridge. Finally, several mixture proportions were investigated for use in the concrete topping.

The proof-of-concept tests were conducted on short cross sections of the beam segments that were joined into two-beam bonded sections with topping and subjected to load testing to emulate transverse bending and shear behavior that correlate to loads in a full-scale finite-element model of a pilot structure. Alternatives both with and without welded bottom flange ties performed better than predicted.



Typical composite cross section dimensions of a inverted-tee beam used for the US 360 Bridge, Figure: Virginia Department of Transportation.

Based on modeling and physical testing, recommendations were made for a full-scale field pilot bridge.

VDOT completed two structures in 2014-2015 with the inverted-tee beam design: one on a high-volume primary highway (US 360 over the Chickahominy River in Henrico County) and one on a suburban secondary road (Towlston Road over Rocky Run in Fairfax County).

The US 360 over the Chickahominy River project incorporated two bridges with identical geometry. One bridge superstructure was constructed using conventional adjacent voided slabs with a composite 7½-in.-thick deck; the second featured the adjacent inverted-tee beam superstructure. Both bridges have two 42-ft-long spans and are jointless; each is constructed with normal-weight concrete in the beams and the deck.

The inverted-tee beams incorporated welded continuous tension ties at the flanges. The 113-ft-wide bridges were built in three stages to meet the maintenance of traffic requirements for this busy primary highway. There is narrow map cracking of similar density in the bridge decks of both bridges that has been attributed to early-age drying shrinkage. The bid price per linear foot for the 6-ft-wide inverted-tee beam was 50% higher than for the 4-ft-wide voided slabs, resulting in the same price per square foot.

The Towlston Road over Rocky Run bridge was a 42-ft-long simple-span two-lane structure with an 11-degree skew and used lightweight concrete in both the inverted-tee beams and in the topping. For the low volume of traffic on Towlston Road, welded flange ties were not deemed necessary. In all other respects the bridge was the same as the US 360 bridge.

One fabricator noted, "The system is certainly much easier to cast than the voided slabs. With some additional refinements. . .this will be the preferred product from the fabricator's perspective." Both inverted-tee beam structures are in excellent condition after the first full year of service with no evidence of cracking in the topping over the prestressed beams related to traffic or environmental loads.

Dr. Carin L. Roberts-Wollmann is a professor at the Charles E. Via Jr. Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University in Blacksburg, Va. Andrew M. Zickler is the complex bridge design and ABC support program manager in the Structure and Bridge Division of the Virginia Department of Transportation in Richmond, Va., and Dr. Michael C. Brown is the associate director of the Virginia Transportation Research Council of the Virginia Department of Transportation in Charlottesville, Va.

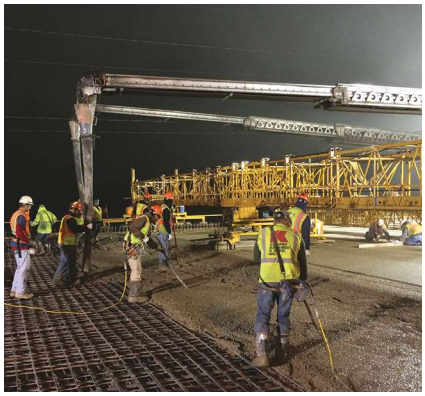
Improving Bridge Deck Service Life

Use of crack-resistant, high-performance concrete bridge decks at the Illinois Tollway

by Steven L. Gillen, Illinois Tollway and Daniel J. Gancarz, Applied Research Associates Inc.

The Interstate 90 bridge over the Fox River is an eight-span structure with an overall length of just over 1300 ft. Photo: Joe Pitlik.

Early age bridge deck cracking is a major concern for transportation agencies, including the Illinois Tollway, which maintains 440 bridge decks ranging in thickness from 7.5 to 8 in. Early age cracking can lead to a reduction in the initiation time of steel reinforcement corrosion and a decrease in service life of the bridge deck. The negative effects of corrosion can be further compounded by freezing and thawing cycles and the use of chloride deicing chemicals. Given the location of the 286-mile Illinois Tollway system in Northern Illinois, bridge decks experience many freezing and thawing cycles each year with deicing chemicals applied for at least 5 months out of the year. These environmental conditions, along with high traffic levels, require durable, crack-resistant concrete in order to maximize the service life of the epoxy-coated steel reinforced concrete bridge decks.



Crack-resistant, high-performance concrete and stainless steel reinforcement were used for the Interstate 90 bridge over the Fox River. Photo: Joe Pitlik.

Prior to 2013, the Illinois Tollway used a prescriptive concrete mixture proportioning approach and had standard superstructure mixtures for bridge decks with a cement content of 605 to 705 pounds of cement per cubic yard. The standard mixtures typically contained either no supplementary cementitious materials or only small amounts of fly ash, and would consist of only one coarse aggregate gradation. This required a concrete with excessive cement paste and, as a result, the mixture was susceptible to shrinkage cracking. Early age cracking was seen on many bridge decks built on the Illinois Tollway since the initial roadways were built and opened to traffic in 1958.

In August 2011, the Illinois Tollway's Board of Directors adopted the 15-year, $12 billion capital program called *Move Illinois: The Illinois Tollway Driving the Future*. The Move Illinois program will improve mobility, relieve congestion, reduce pollution, and link economies across Northern Illinois. It includes rebuilding and widening the Jane Addams Memorial Tollway (Interstate 90); constructing the all-electronic Elgin O'Hare Western Access Project; constructing a new interchange to connect the Tri-State Tollway (Interstate 294) to Interstate 57; and many other system-wide projects to keep the existing tollway system in good repair. These projects will require the reconstruction or construction of more than 100 bridges. Tollway bridge decks built before 2013 have been shown to have a typical service life of only 20 to 35 years before the need for repeated deck or joint repairs begin. They also have a total life of only 35 to 50 years before a complete deck replacement is needed.

Initial research was conducted by CTLGroup and the University of Illinois at Urbana-Champaign in 2012 and 2013 with the objective of extending the service life of Illinois Tollway bridge decks. That research developed mixture-proportioning specifications that would produce a deck concrete with minimal shrinkage cracking potential and with moderate resistance to chloride penetration. The Illinois Tollway elected to take a performance approach for high-performance concrete (HPC) bridge deck mixture proportions compared to the prescriptive approach that was used in the past, and is

Table 1. Mixture designs developed as part of Illinois Tollway research

Mixture ID	Bridge Superstructure	Concrete Mixture with Optimized Aggregate Gradation	SLF	SRA	Ternary Optimized Gradation with SLF and SRA
Material	lb/yd³ (saturated surface dry)				
Cement	515	375	409	403	313
Fly Ash	0	125	0	134	111
Slag	110	0	136	0	154
Coarse Aggregate (CM-11)	1875	1501	1714	1840	1245
Coarse Aggregate (CM-16)	0	391	0	0	325
Saturated Light-weight Fines	0	0	364	0	236
Fine Aggregate	1160	1370	986	1323	1039
Water	263	210	237	226	220
Total Cementitious Content	625	500	545	536	578
w/cm (including water in admixtures)	0.43	0.43	0.44	0.43	0.39

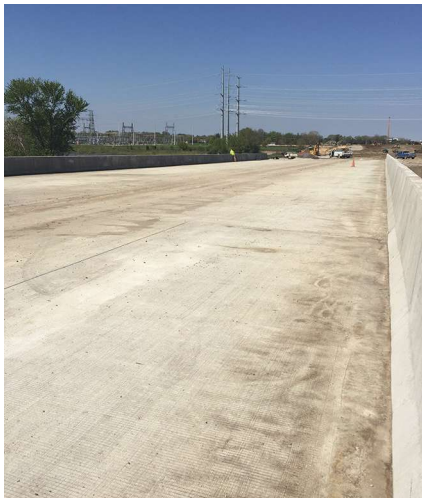
Note: CM-11 is an Illinois Department of Transportation (IDOT) coarse aggregate gradation number corresponding to a nominal maximum aggregate size of ¾ in.
CM-16 is an IDOT coarse aggregate gradation number corresponding to a nominal maximum aggregate size of ⅜ in.
SLF = saturated lightweight fines; SRA = shrinkage-reducing admixture; *w/cm* = water-cementitious materials ratio.

still used by most transportation agencies today. In addition to using approved materials, limits were set for compressive strength, slump, linear shrinkage, restrained ring shrinkage, freezing and thawing cycles, alkali-silica reactivity, and chloride ion penetration. Minimum cement contents and maximum water-cementitious materials ratios (*w/cm*) were not specified. Testing was required on laboratory-prepared and field-trial batch produced samples to ensure performance and verify that the proposed mixture could be produced at the concrete plant. Table 1 summarizes the mixture designs tested as part of the research. The top-three performing mixture proportions for shrinkage resistance contained saturated lightweight fines (SLF), shrinkage-reducing admixture (SRA), or ternary optimized gradation with SLF and SRA (ULT). Based on these results, all HPC mixtures were required to contain SLF or SRA to mitigate shrinkage cracking.

Since 2013, 77 bridges have been built with the Illinois Tollway's crack-resistant HPC special provision. Isolated cracking, most of it caused by restraint cracking due to temperature differentials between the deck and steel beams, has been identified on 24 of the bridges. Shrinkage cracking due to insufficient curing for a given concrete mixture has only been identified on seven of the 42 bridges.

There have been no verifiable constructability issues with these crack-resistant HPC mixtures. The mixtures are commonly placed using a pump or belt conveyor. The SLA and SRA materials used on the Illinois Tollway have had little effect on the fresh properties or finishing. For the major Illinois Tollway bridges over waterways or at interstate-to-interstate interchanges, stainless steel reinforcement is being used within the decks along with the shrinkage crack-resistant HPC to provide a deck service life that will exceed 75 years.

The Illinois Tollway is currently in the process of further improving the service life of crack-resistant HPC for use with epoxy-coated reinforcement. This will be achieved while maintaining the crack resistance and constructability of the mixture. At this point, two options are being considered. This includes lowering the threshold for the chloride ion penetration test, thus requiring a denser, less permeable ternary mixture and/or requiring the use of a corrosion inhibiting admixture. This work is being done as a joint effort between the Illinois Tollway, CTLGroup, and Tourney Consulting Group LLC. It will be using recently developed computer software to most accurately predict the service life of Illinois Tollway HPC bridge decks for the structural design, mixture properties, and climatic conditions that exist. The objective of this work is to ultimately develop specifications for crack-resistant HPC mixture proportions that—when combined with efficient preservation work—will provide epoxy-coated steel reinforced concrete bridge decks with service lives of at least 50 years before any repairs are needed, and total service lives that match the life of adjacent new pavements of around 75 years. By taking a holistic systems approach to materials selection, the Illinois Tollway plans to attain durable, cost-effective structures with service lives of 75 years.



Crack-resistant high-performance concrete was used for the IL 390 decks over Salt Creek. Photo: Supraja Reddy.

The Illinois Tollway has achieved consistent success since adopting crack-resistant HPC for bridge decks in 2013. With the help of consultants, researchers, and the concrete industry, the Illinois Tollway plans to continue improving the service life of bridge decks.

Steven L. Gillen is the deputy program manager of materials for the Illinois Tollway in Downers Grove, Ill., and Daniel J. Gancarz is a project engineer for Applied Research Associates Inc. also in Downers Grove.

A PROFESSOR'S PERSPECTIVE

NONCONTACT SPLICES

Strut-and-tie method, history, and a few additional thoughts

by Dr. Oguzhan Bayrak, University of Texas at Austin

Noncontact splices are frequently encountered in bridge substructures and designed according to the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[1] These specifications limit the splice offset (shown in Fig. 1) in flexural members to one fifth of the required splice length or 6 in. For columns with longitudinal bars that anchor into oversized shafts, this spacing restriction is waived, provided that a sufficient amount of transverse reinforcement is provided in the shafts. The splice offset limits for flexural members referenced above exist in recognition of the limitations that exist in the available test data. The supplementary requirements that exist for the specific case of column to shaft connections stem from test data for one specific application that became available after the introduction of original provisions. Lack of a broad range of test data on noncontact splices notwithstanding, within this article I would like to use the load transfer mechanism in noncontact lap splices to show the transparency in using the strut-and-tie method (STM) and provide a brief historical context.

Figure 1 shows the mechanics of the load transfer in a typical noncontact splice. As can be observed in this figure, the development of a compression field between the longitudinal bars that are involved in the force transfer is necessary. The inclination of this compression field (or struts) is a function of the tension force in the bars T, the quantity of transverse reinforcement provided A_{tr}, the splice length, and the splice offset s. With that stated, let us examine some of these variables. To begin, we must recognize that the length of a noncontact splice is adversely influenced by the splice offset distance s. As the splice offset gets larger, so does the splice length. In a case where the diagonal compression field makes a 45-degree angle with the longitudinal bars, the splice length is equal to the summation of basic development length "$l_d + s$."

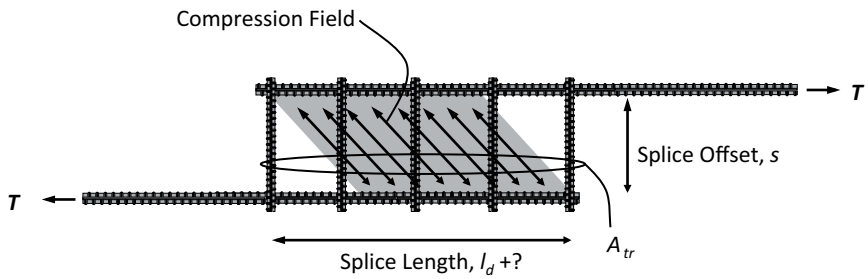


Figure 1. Mechanics of load transfer in noncontact splices. All Figures: Oguzhan Bayrak.

The force triangles presented in Fig. 2 clearly demonstrate the role of additional transverse reinforcement. When the quantity of transverse reinforcement is doubled, the angle between the compression field and the longitudinal reinforcement increases (for example, $\theta_2 > \theta_1$). As this angle increases, the overall length of the noncontact splice decreases, as can be inferred from Fig. 1. In other words, a designer can use a shorter noncontact splice length by using an increased amount of transverse reinforcement. Conversely, a lesser quantity of transverse reinforcement can be used, if the structural geometry allows for the use of a greater splice length.

Additional observations that can be made by examining the force transfer mechanism shown in Fig. 1 and 2 include: as the tension force T gets larger, that is, as the size of the bar being spliced gets larger, so does the splice length; and small portions at the ends of the bars being spliced do not contribute to the force transfer, as dictated by equilibrium. It is important to note that the qualitative discussion provided previously did not include any hard limits placed on the splice offset distance or on any other aspect of noncontact splice design. Rather, the discussion was based on first principles.

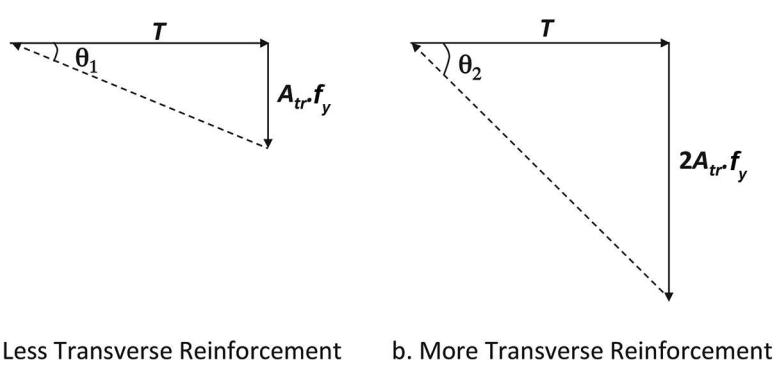


Figure 2. Force triangles for noncontact splice: influence of transverse reinforcement.

Typically, the limits placed on code provisions reflect the bounds of our understanding and/or the limits of test data available. In this context, ACI 408R-03[2] provides an informative summary of the historical developments that surrounded the evolution of reinforcing bar splicing in the United States. According to this reference document, until the 1963 edition of ACI 318, contact splices were not permitted and a minimum reinforcing bar offset (that is, the distance between the spliced bars) of $1.5d_b$ was required in ACI 318-47.[3] In 1951, the minimum bar offset requirement was reduced to a value of $1.0d_b$ and then in the 1963 edition of ACI 318, both contact and noncontact splices were allowed. In 1971, a maximum reinforcing bar offset requirement of 6 in. or one fifth of the required spliced length was introduced into ACI 318. The thinking behind this provision was that, with this conservative limit in place, a zig-zagging crack with 1:5 inclination could not form and structural safety in a noncontact splice would be ensured. More importantly, it is essential to appreciate that the commentary provided in ACI 318 openly acknowledges the fact that the 6 in. maximum spacing (that is, the limit placed on the spliced bar offset) was introduced because "most research available on lap splices of deformed bars was conducted with reinforcement within this spacing."

Moving forward, the benefits of generating additional data to fill the gaps in our knowledge cannot be overlooked. With that stated, the benefits of looking at the noncontact splice problem with the STM are also clear. These observations provide support to the increased emphasis placed on the use of the STM in the *AASHTO LRFD Bridge Design Specifications*. Consistent with that emphasis, I will cover this topic with a few more examples in upcoming articles.

References:

1. AASHTO. 2010. *AASHTO LRFD Bridge Design Specifications*, 7th ed. with 2015 and 2016 interim revisions. American Association of State Highway and Transportation Officials, Washington, D.C.
2. ACI 408R-03. 2012. *Bond and Development of Straight Reinforcing Bars in Tension*. Reported by ACI Committee 408, reapproved. American Concrete Institute (ACI), Farmington Hills, Mich.
3. ACI 318. 1947, 1963, 1971, 2014. *Building Code Requirements for Structural Concrete and Commentary*. ACI, Farmington Hills, Mich.

EDITOR'S NOTE

Dr. Bayrak's research group at the University of Texas at Austin assembled a large data set of concrete shear tests to validate the strut-and-tie code provisions. This research forms the basis of new strut-and-tie modeling design provisions in the AASHTO LRFD Bridge Design Specifications. *He will be sharing other research findings regarding modeling and the intricacies of node and strut definitions in upcoming articles. If you have a question about strut-and-tie modeling, please submit your question at the* ASPIRE *website.*

Taking Ultra-High-Performance Concrete to New Heights

The Malaysian Experience

by Dr. Maher K. Tadros, e.construct.USA LLC and Dr. Yen Lei Voo, DURA Technology

Ultra-high-performance concrete (UHPC) was first introduced as reactive powder concrete in the early 1990s by the French contractor Bouygues.[1] When introduced, it came in two classes, Class 200 MPa (29 ksi) and 800 MPa (116 ksi). Since then, much research has been performed by the Federal Highway Administration (FHWA)[2] and researchers in other countries around the world, including Australia, Austria, Canada, Croatia, France, Germany, Italy, Japan, Malaysia, the Netherlands, New Zealand, Slovenia, South Korea, Spain, Switzerland, and the United Kingdom. In the United States, several state departments of transportation have expressed interest in using UHPC in their bridge projects, supported by FHWA research as well as that done by their local universities. Most notably, Virginia has produced I-beams with UHPC and Iowa has built two bridges with UHPC beams and one with a UHPC deck. A significant interest has recently been directed at using UHPC in longitudinal joints between precast concrete beams.

It appears that the high cost of UHPC has discouraged owners from implementing use of this outstanding material in applications beyond the initial demonstration projects, most of which had been subsidized by government technology implementation programs. The exception to this trend has been the significant success of the company DURA Technology (DURA) in Malaysia. Over 70 bridges have been built by DURA in that country since 2010. This article provides a summary of the steps taken by DURA to develop solutions with UHPC that are cost-effective on a first-cost basis. When the superior durability of UHPC is factored in, its value increases dramatically.

What is UHPC?

There is no universal definition of UHPC or even its name. It appears that a commonly used name and definition in the United States is the one introduced by Graybeal[3]: "UHPC-class materials are cementitious-based composite materials with discontinuous fiber reinforcement, compressive strengths above 21.7 ksi (150 MPa), pre-and post-cracking tensile strengths above 0.72 ksi (5 MPa), and enhanced durability via their discontinuous pore structure." In comparison, conventional concrete is without fibers and typically has a compressive strength of 4 to 10 ksi.

The ingredients of a UHPC mixture can vary. Early mixtures generally consisted of about 1200 lb/yd^3 (700 kg/m^3) of portland cement, 25% silica fume, 25% silica powder, and fine sand with maximum grain size of 0.03 in. (0.8 mm). A very low water-binder ratio of 0.16 to 0.20 was used. For flowability, a large quantity of high-range water-reducing admixture must be used. Steel fibers in the amount of about 2 to 2.5% by volume are used. The fibers are cut from very fine, 360 ksi (2500 MPa) wire. Other mixtures have been developed; for example, Tadros et al.[4] report on a mixture that uses local aggregates and has a cost that is about 10% of the cost of early UHPC mixtures. However, this mixture does not strictly meet the definition of UHPC because the compressive strength is only 18 ksi (124 MPa).

Factors Inhibiting Widespread Use of UHPC

The original prebagged UHPC product introduced to the U.S. market had tight tolerance specifications. The steel fibers had to be imported from abroad, which required a waiver of Buy America requirements for many projects. As a result, the unit cost was relatively high. In addition, the UHPC was expected to be mixed in high-energy mixers for 8 to 17 minutes, plus another 10 min. for loading the mixer and unloading the mixture into a ready-mix truck or other transportation devices. However, Graybeal[3] has reported that mixing of UHPC can be performed using conventional mixers, as long as high energy input is provided. Temperature of the mixture, due to increased mixing time, can be controlled through use of ice water. The steel fibers are now available from a manufacturer in the United States.

Upon placement, the early development of UHPC called for curing for at least 48 hours at a high, 90°C (194°F), temperature. Some of the original mixtures were also required to be cured in high-pressure chambers. This is inconsistent with standard practice of 12- to 16-hour, overnight curing with maximum temperatures of 70°C (158°F). Loss of productivity and high materials costs could result in a premium of 400% or more of the cost of conventional concrete. This sharp increase cannot be offset by the anticipated reduction in total quantities. Wille et al.[5] have demonstrated that an optimized mixture can achieve the required strength without the originally required heat or pressure curing.

An effort is urgently needed in the United States to publish American Association of Highway and Transportation Officials (AASHTO) specifications for design and construction with UHPC. Australia, France, Japan and most recently Switzerland have already published design recommendations and model code language.

The Malaysian Experience

Introduction of UHPC in Malaysia was started by a couple of engineers in 2006. The company DURA was co-founded by Dr. Yen Lei Voo after he completed his Ph.D. in Australia on the topic of UHPC. His advisor was Professor Stephen Foster, who had been championing UHPC in Australia. Interestingly, the use of UHPC in Australia has stagnated since the construction of its first bridge, the Shepherd Gully Creek Bridge,

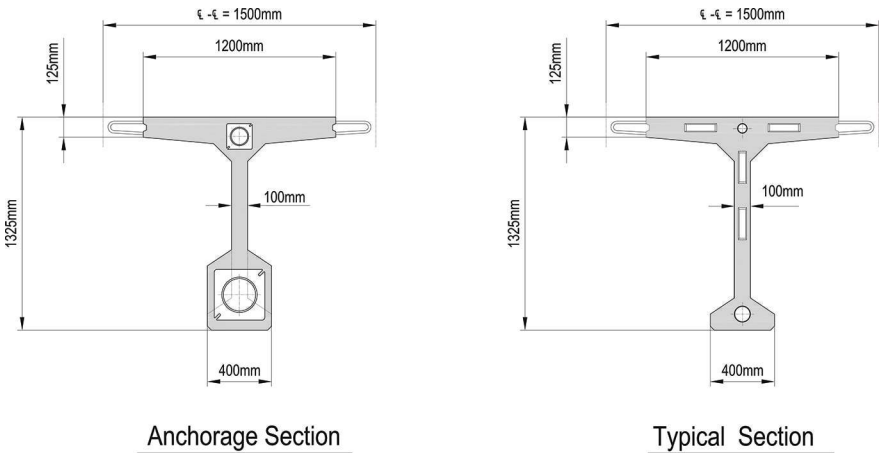


Figure 1. Decked bulb-tee section used in the Sungai Nerok Bridge. All Figures and Photos: DURA Technology. Note: 1 in. = 25.4 mm.

in 2003. The initial Australian experience has paralleled that in the United States and Canada where small demonstration projects did not create the anticipated acceptance. DURA's pioneers started with an intensive research program from 2006 to 2010, supported by the Malaysia Public Works Department. The research program yielded important optimization factors:

- The constituent materials were reduced to cement, silica fume, sand, high-range water-reducing admixture, and water. Further, relatively low-cost steel fibers were identified. As a result, the original \$2600/m^3 (\$2000/yd^3) cost was reduced to about \$600/m^3 (\$460/yd^3).

- A large, 12 m^3 (15.7 yd^3) single shaft ribbon blender was used for mixing powder and highly viscous materials. The precast concrete product was sized so that it could be produced with only one batch of UHPC; piece weights were limited to about 20 tonnes (22 tons). There is no waiting for the next batch, and no concern for differential setting time, thermal gradient, or shrinkage between batches. There are counter-intuitive benefits to making relatively small pieces, such as:

    - The UHPC is mixed in one cycle using the large mixer.
    - The precast elements can be made in a small, indoor facility.
    - The precast elements can be shipped in enclosed trucks and shipping containers.
    - The precast elements can be handled at the jobsite with small equipment.

- Four standardized cross-section shapes were created: pretensioned decked I-beams for short spans, spliced I-beams and segmental U-girders for medium spans, and segmental box-girders for long spans. The longest span constructed to date is 100 m (328 ft).

Figure 2. Rantau-Siliau Bridge during construction.

- Straight pretensioning was used where possible. However, most applications involve spliced post-tensioned beams, using straight bottom flange post-tensioning. The segment interfaces are match-cast, with shear-keyed joints.

- Each UHPC batch was required to achieve a 1- and 28-day average compressive (cube) strength of 70 MPa (10 ksi) and 165 MPa (24 ksi), respectively, and for an average flexural strength at 28 days of 25 MPa (3.6 ksi).

- Most significantly, perhaps, is that curing was simplified such that the standard precast, prestressed concrete 1-day cycle is maintained. Once the strands are detensioned, the product is subjected to additional curing without losing production efficiency.

These measures have resulted in highly successful and a rapidly growing number of UHPC bridges, with lower initial cost than conventional construction and with a life expectancy far exceeding the 100 years desired by the design community. The number of completed bridges has increased from one bridge in 2010 to 2, 5, 14, 16 and 37 in 2011, 2012, 2013, 2014, and 2015, respectively. The year 2016 is expected to continue to break records with 32 bridges already completed or under construction.

Example Bridges[6]

The Sungai Nerok Bridge has three 30-m-long (98 ft) spans and is 15 m (49 ft) wide. Each span has 10 beams spaced at 1.5 m (5 ft) center to center. Each beam was made of two identical decked bulb-tee halves (Fig. 1) spliced with nineteen 0.6-in.-diameter (15.2 mm) strands in a single bottom post-tensioning tendon and four 0.6-in.-diameter (15.2 mm) strands in the top tendon. Each beam weighed 29 tonnes (32 tons). The web was only 100 mm (3.94 in.) wide. It had no reinforcing bars except at the ends in the post-tensioning anchorage zones. The longitudinal connections between flanges were made with conventional reinforcement and cast-in-place UHPC closure placements.

The Rantau-Siliau Bridge has a single span 52 m (170 ft) long and is 18.3 m (60 ft) wide. The cross section has five 1.75-m-deep (5.87 ft) U-beams (Fig. 2

and 3). The U-beam ends were encased in the conventional concrete of the integral abutments. Conventional reinforcement was used only in the anchorage zones and to connect the girders to the 200-mm-thick (7.9 in.) cast-in-place, conventional concrete deck.

Each U-beam consists of intermediate 8-m-long (26.2 ft) segments and two end segments that are 5.75 m (18.9 ft) long, weighing 18 and 16.5 tonnes (19.8 and 18.2 tons), respectively. Post-tensioning of each U-beam consisted of four bottom tendons each with twenty-seven 0.6-in.-diameter (15.2 mm) strand and two top tendons with four 0.6-in.-diameter (15.2) strand.

The record breaking 100-m-long (328 ft) bridge at Batu 6, Gerik, was completed in 2015. This segmental box-girder bridge has thirty-six 2.5-m-long (8.2 ft) standard intermediate segments and four anchorage segments (Fig. 4). The standard segment weighs 17 tonnes (18.7 tons).

Conclusion

UHPC is a fascinating new material, featuring very high compressive and tensile strengths and excellent durability. Since its introduction in the early 1990s, various countries have attempted to introduce it to bridge construction, with limited success. Initial high unit costs and perceived production and design difficulties have contributed to its slow adoption.

However, DURA in Malaysia has developed successful techniques for cost-effective solutions. By producing pieces no heavier than 20 tonnes (22 tons), reducing the precast bed production cycle to the conventional 1 day, and optimizing the UHPC mixture proportions to produce the required properties at a fraction of the cost of previous mixtures, it has been possible to build up to 70 bridges in the past 5 years.

References

1. Richard, P. and M. H. Cheyrezy. 1993. "Reactive Powder Concretes with High Ductility and 200-800 MPa Compressive Strength," *ACI SP-144: Concrete Technology: Past, Present, and Future*, American Concrete Institute, Detroit, MI. SP-144, pp: 507-518.
2. Russell, H. G. and B. A. Graybeal. 2013. "Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community," Publication No. FHWA-HRT-13-060, National Technical Information Service, Springfield, VA. 171 pp.
3. Graybeal, B. 2011. "Ultra-High Performance Concrete," *TechNote,* FHWA-HRT-11-038, Federal Highway Administration, McLean, VA.
4. Tadros, M. K. and G. Morcous. 2009. "Application of Ultra-High Performance Concrete to Bridge Girders," Nebraska Department of Roads (NDOR) Project Number P310, Lincoln, NE. February, 72 pp.
5. Wille, K., A. E. Naaman, and S. El-Tawil, S. 2011. "Optimizing Ultra-High-Performance Fiber-Reinforced Concrete," *Concrete International*, Vol. 33, No. 9, September, pp. 35-41.
6. Voo, Y. L., S. J. Foster, and M. F. Hassan. 2014. "The Current State of Art of Ultra-High Performance Concrete Bridge Construction in Malaysia," *Proceedings of the 12th International Conference on Concrete Engineering and Technology 2014* (CONCET 2014), Selangor, Malaysia, August 12-14, pp. 95-102.

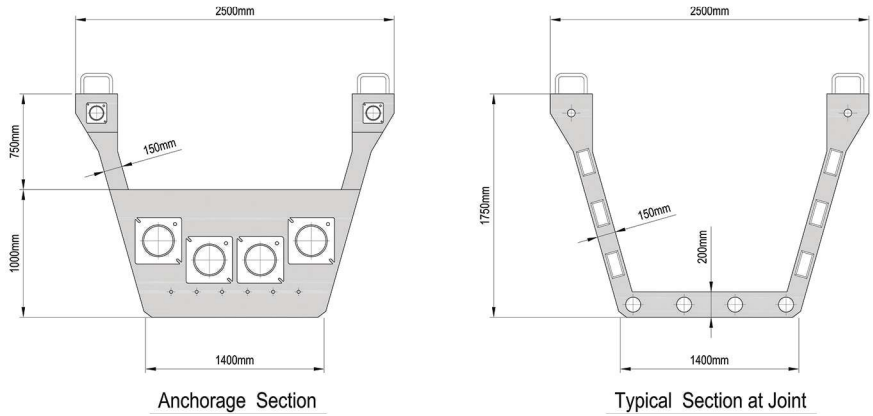


Figure 3. Details of ultra-high-performance concrete U-beams cross section.

Dr. Maher K. Tadros is a PCI Titan and principal of e.construct.USA, LLC in Omaha, Neb,. and Dr. Yen Lei Voo is founder and CEO of DURA Technology Sdn Bhd, Malaysia.

EDITOR'S NOTE

Further discussions with Dr. Voo reveal this type custom industrial mixer (single shaft ribbon blender) may be found at http://www.sowergroup.com/instruction_detail/&productId=115.html

Figure 4. Batu 6 segmental box-girder bridge with 100 m (328 ft) span.

New FHWA Post-Tensioned Box Girder Design Manual

by Reggie Holt, Federal Highway Administration, and John Corven, Corven Engineering

The Federal Highway Administration (FHWA) is pleased to announce the release of a new manual for the analysis and design of concrete box-girder bridges. The *Post-Tensioned Box Girder Design Manual* was developed as a part of the FHWA project Advancing Steel and Concrete Bridge Technology to Improve Infrastructure Performance. Brian Kozy and Reggie Holt of FHWA are providing direction to the project team led by Lehigh University and that includes Corven Engineering. The author of the manual is John Corven of Corven Engineering.

The *Post-Tensioned Box Girder Design Manual* focuses on cast-in-place, post-tensioned concrete box-girder bridges with superstructure cross sections similar to those shown in Fig. 1. The manual serves as a resource to state departments of transportation and consulting firms that are exploring the benefits of, or are looking for guidance on, using this method of bridge construction.

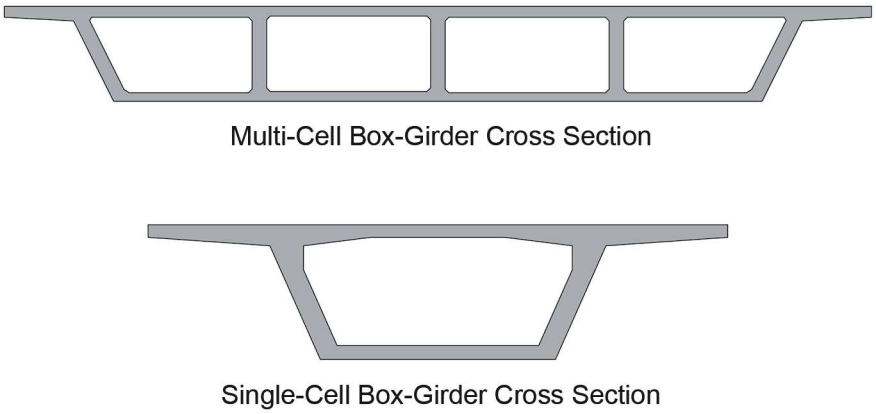


Figure 1. Typical concrete box-girder cross section. All Figures: Developed by Corven Engineering for the Federal Highway Administration.

Introductory Chapters

The FHWA *Post-Tensioned Box Girder Design Manual* was developed for engineers who have limited exposure to the design and construction of prestressed concrete bridges. Chapter 1 presents a brief history of the use of the bridge type and describes the basic components of a box-girder superstructure. Typical geometries of post-tensioning tendons for cast-in-place concrete bridges are also presented in Chapter 1, along with descriptions and photographs of the components that comprise a post-tensioning tendon. This chapter concludes with an overview of the construction of cast-in-place concrete box-girder superstructures.

Material characteristics of the concrete and prestressing steel are presented in Chapter 2 of the manual. Pertinent time-dependent characteristics in accordance with the *CEB-FIP Model Code* (1990) of the concrete (creep and shrinkage) and the prestressing steel (relaxation) are presented. Design provisions of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* that address prestress losses related to time-dependent material characteristics are presented in a later chapter.

Prestressing with Post-Tensioning

Two chapters of the manual deal with the mechanics of prestressing a girder with post-tensioning. Chapter 3 presents typical stress summaries that are the result of girder self-weight, superimposed loads, and post-tensioning. Equations for the summation of total stress are then rearranged in two useful ways, so that the prestressing force required at a cross section can be found directly for a given tendon eccentricity and the permissible limits of eccentricity can be found for a given prestressing force. Figure 2, taken from Chapter 3, graphically depicts the first of these two, where the internal moment resulting from the prestressing, taken about the upper kern, is equated to the externally applied bending moment. Chapter 3 also presents the geometric features of post-tensioning tendons comprised of a series of parabolic profiles, the tendon geometry most commonly used in cast-in-place concrete box-girder construction. These geometric features are then used to evaluate secondary moments due to the prestressing of continuous-span girders.

Losses in prestress resulting from tendon friction, wobble, anchor set, and elastic shortening are developed and presented in Chapter 4. The calculation of tendon elongations is presented in this chapter, as well as lump-sum time-dependent losses in prestressing force as predicted by applicable AASHTO LRFD guidelines. Considerations for single-end and two-end stressing are discussed. Figure 3, taken from Chapter 4, shows a typical tendon force diagram along the length of a three-span, post-tensioning tendon after two-end stressing and anchor set.

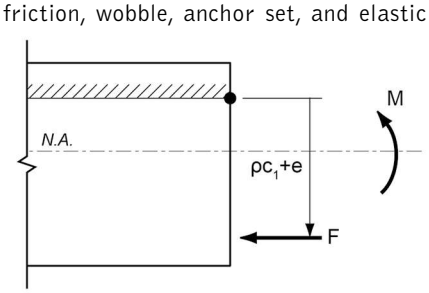


Figure 2. Equilibrium of internal and external moments.

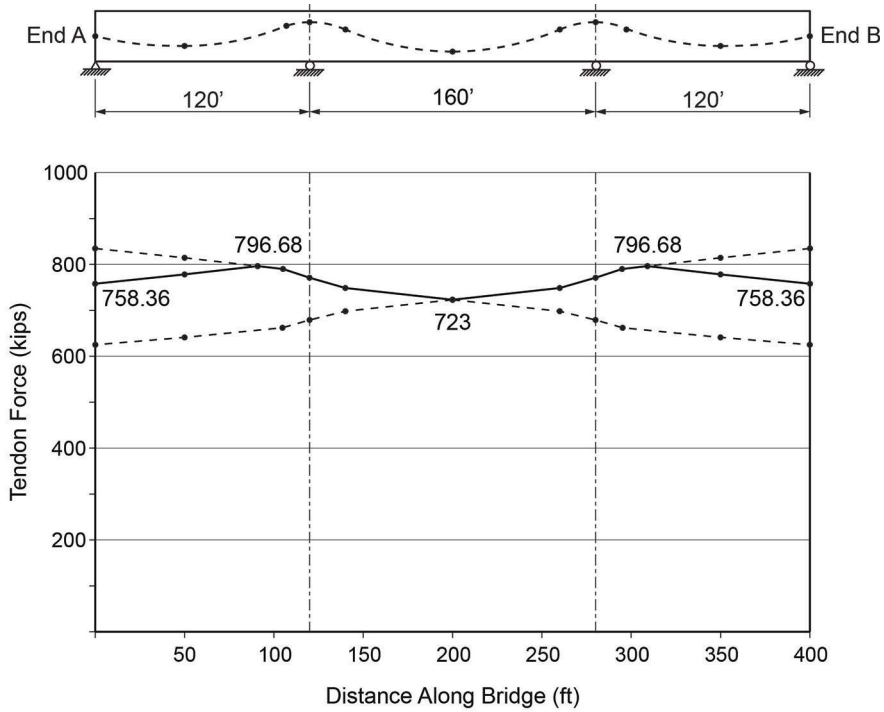


Figure 3. Tendon force diagram after stressing from both ends.

Preliminary Design

Chapter 5 walks through the preliminary design process for a cast-in-place, post-tensioned box-girder bridge using a three-span continuous bridge as an example. Guidelines for the dimensions of the box-girder superstructure, both of the overall girder and the members of the cross section, are presented. This is followed by the longitudinal analysis of the bridge to determine bending moments at critical sections. Post-tensioning tendon profiles and the number of strands in the tendons are selected based on the required prestressing force at each critical section. The jacking force of the tendons (P_{jack}) is established based on understanding the force in the tendon along its length. Finally, service limit states are verified, substantiating the preliminary design.

Cast-in-place box-girder bridges are often constructed monolithically with supporting columns. Chapter 6 presents additional design considerations when the substructure is integral with the superstructure. Superstructure bending moments caused by the restraint of the integral substructures are evaluated. The load cases discussed include temperature rise and fall, temperature gradient, concrete creep, and concrete shrinkage.

Final Design

Chapters 7, 8, and 9 of the *Post-Tensioned Box Girder Design Manual* focus on final design. Longitudinal superstructure analysis and design are addressed in Chapter 7. Guidelines for computer modeling of post-tensioned box girders are presented in this chapter. Modeling concepts for straight and curved bridges, with or without integral substructures, are discussed. Final design is presented by continuing the design of the bridge for which preliminary design was developed in Chapter 5. The mechanics of cross-section ultimate capacities with regard to flexure and shear are developed. The chapter concludes with the verification of strength limit states in accordance with the AASHTO LRFD specifications.

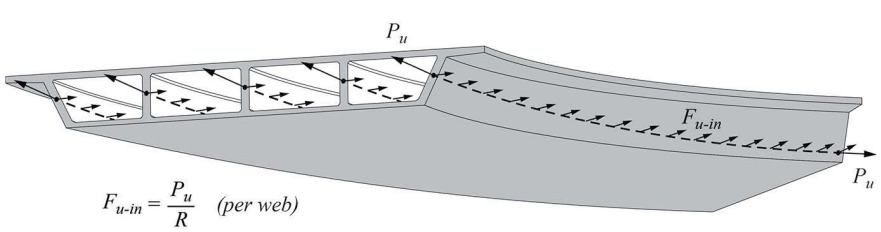


Figure 4. Effects of tendons in curved concrete members.

Box-girder superstructures require analysis and design in the transverse direction. Chapter 8 presents both the approximate design method from the AASHTO LRFD specifications and a generalized approach to transverse analysis and design for single-cell box-girder superstructures.

Chapter 9 presents three important design considerations for post-tensioned box-girder bridges, beginning with a detailed look into the local behavior of tendons in curved concrete members, depicted in Fig. 4. Both in-plane and out-of-plane force effects and resistances are presented. This information is followed by a discussion of end anchorage zones and the transfer of superstructure loads to the substructure through diaphragms for both nonintegral and integral superstructures.

Useful Appendices

The *Post-Tensioned Box Girder Design Manual* includes four useful Appendices. Appendix A presents a hand method of structural analysis of indeterminate structures—the Method of Joint Flexibilities. This flexibility-based method, which relates simple-span girder rotations to continuity moments in continuous structures, is an excellent tool for analyzing post-tensioned structures where tendon paths are quickly integrated as curvature diagrams to produce simple span end rotations. Appendix B presents fundamental torsional characteristics of single- and multi-cell box-girder structures. Equations for shear flow and the torsional constant for cross sections are presented in this Appendix. Appendices C and D contain design examples for three-span continuous bridges.

No Cost Download

The *Post-Tensioned Box Girder Design Manual* can be downloaded from the FHWA at no cost at https://www.fhwa.dot.gov/bridge/concrete/. This website contains many excellent bridge analysis and design resources.

Reggie Holt is a senior structural engineer at the Federal Highway Administration in Washington, D.C. John Corven is the president and chief bridge engineer for Corven Engineering Inc. in Tallahassee, Fla.

Repairing and Protecting Concrete Piles with Galvanic Jackets

by J. Christopher Ball, Vector Corrosion Services

From small county roads to major highways, a significant number of bridges are built over coastal waters. With exposure to the seawater environment, these structures are at risk of premature corrosion of the reinforcing steel. In particular, conventionally reinforced and prestressed concrete piles in seawater are subjected to high levels of chloride contamination leading to serious deterioration and on-going maintenance repairs.

Concrete Pile Corrosion

Concrete piles in seawater are exposed to three distinct exposure conditions:

- Atmospheric (Dry)—elevated sections of concrete piles are subject to airborne chloride deposition. Once critical concentrations of chloride are present on the steel surface, the passive oxide layer is defeated and corrosion initiates.
- Splash/tidal (Wet/Dry)—the splash and tidal zones are intermittently subjected to seawater saturation and are at high risk of corrosion due to wet-dry chloride exposure cycles.
- Submerged (Wet)—underwater sections of piles are less frequently affected by corrosion damage. This is due to seawater having low levels of dissolved oxygen, a precondition for corrosion because oxygen is necessary at the cathodic sites to facilitate the reduction reaction ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$).

Figure 1. Corrosion of prestressed pile in tidal/splash zone. All Photos and Figures: Vector Corrosion.

Figure 2. Fabric form jacket with concrete fill.

Pile Jacketing

In an effort to repair, protect, and extend the life of corroding concrete piles, damaged piles have been jacketed with

- an overbuilt layer of reinforced concrete,
- cement-grout-filled stay-in-place forms (fiber-reinforced polymer [FRP], corrugated steel, or fabric), or
- epoxy-grout-filled FRP jackets.

In the 1990s, it was documented that this type of jacketing was ineffective for chloride contaminated concrete piles as it allowed corrosion to continue and the jacketing concealed the pile damage from detection by visual inspection.

In 1998, research conducted for the Florida Department of Transportation concluded that only jacketing that included cathodic protection should be permitted and this was implemented as policy.[1] The Virginia Transportation Research Center also reported in 1999 that "Grout jacketing alone is an inadequate protection against corrosion and should be supplemented with cathodic protection (CP)."[2]

Cathodic Protection Jacketing

Cathodic protection jackets can employ impressed current cathodic protection (ICCP) or galvanic anodes. ICCP is effective but requires a permanently operating power supply and commitment to system monitoring. The importance of ICCP system monitoring cannot be overemphasized, especially when applied to prestressed concrete where overprotection can cause corrosion or hydrogen embrittlement of steel tendons.[3]

In the battle against pile corrosion, galvanic jackets are an effective, low-maintenance option for the bridge preservation engineer. Galvanic jackets are installed using zinc anodes that are directly connected to the steel or connected via an

Galvanic Jacket Anode Options

Exposure	Wetness	Wet Jacket	Dry Jacket
Atmospheric	Dry		AA
Splash /Tidal	Intermittent	BZ or AA	BZ or AA
Submerged	Wet	BA	BA

BA - Bulk Zinc Anode in Seawater
BZ - Bare Zinc Anode (Seawater Activated)
AA - Self-Activated Anode

Table 1. Galvanic jacket anode options.

exterior electrical junction box. Galvanic jackets can include additional reinforcing steel if structural strengthening is required to supplement corroded reinforcement.

Galvanic Jacketing

Wet Applications

Different types of galvanic jacket systems are available today (Table 1). Typical galvanic jackets that are appropriate for wet exposure in the splash/tidal and submerged zones (that is, wet jacket) contain high purity bare-zinc anodes (BZ) inside a stay-in-place FRP form with a bulk zinc anode (BA) attached to the submerged section of the pile (Fig. 3 and 4). Once the jacket is in place, the annulus containing the bare-zinc anodes is filled with portland cement grout or concrete. The FRP jacket, which is placed 1 ft below low tide, is continuously submerged in seawater. With an open-bottom design, seawater is allowed to penetrate inside the jacket through direct saturation and capillary diffusion. This keeps the concrete highly conductive and exposes the zinc anodes to chlorides thus keeping the zinc electrochemically active (chloride activation). The bulk zinc anode produces a small DC current that cathodically protects the submerged sections of the pile and supplements the zinc anodes inside the jacketed area.

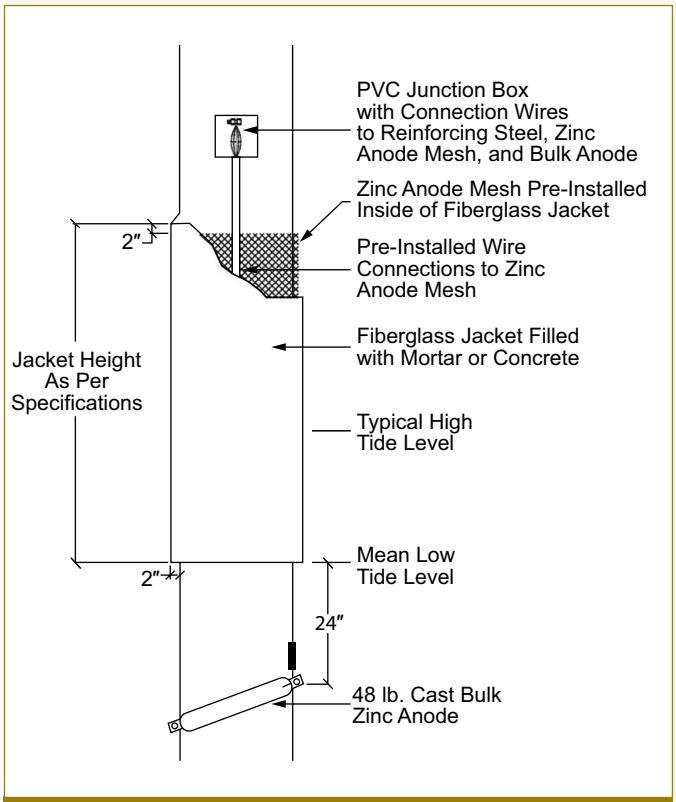


Figure 3. Schematic of wet jacket including bare zinc mesh anode, stay-in-place fiber-reinforced-polymer form, and submerged bulk zinc anode.

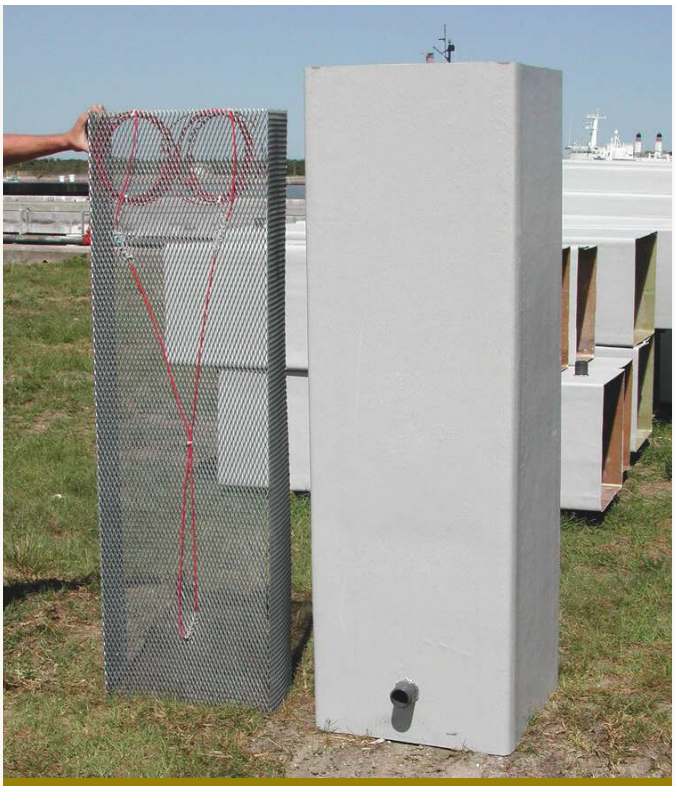


Figure 4. Wet jacket that includes a bare zinc mesh anode and stay-in-place fiber-reinforced-polymer form. (Bulk zinc anode not shown.)

Because bare-zinc jackets rely on saltwater saturation, they are less effective at protecting drier areas of concrete piles or piles exposed to low chloride water or freshwater. Bare-zinc jackets provide a high level of protection in the tidal and splash zones where the zinc anodes and grout infill are directly saturated in saltwater.

Dry Applications

A different type of galvanic jacket uses premanufactured self-activated anodes (AA) placed inside stay-in-place forms with portland cement grout or concrete infill. Self-activated anodes (that is, not saltwater/chloride activated) function by keeping the zinc in a highly alkaline environment that is corrosive to zinc but not to reinforcing steel. This technology facilitates anode operation independent of exposure to seawater or chloride saturation (Fig. 5) and can be used in dry applications (that is, dry jacket) such as severely damaged bridge columns or piles above high tide. If the concrete section to be protected is only in a dry, atmospherically exposed area, then a dry

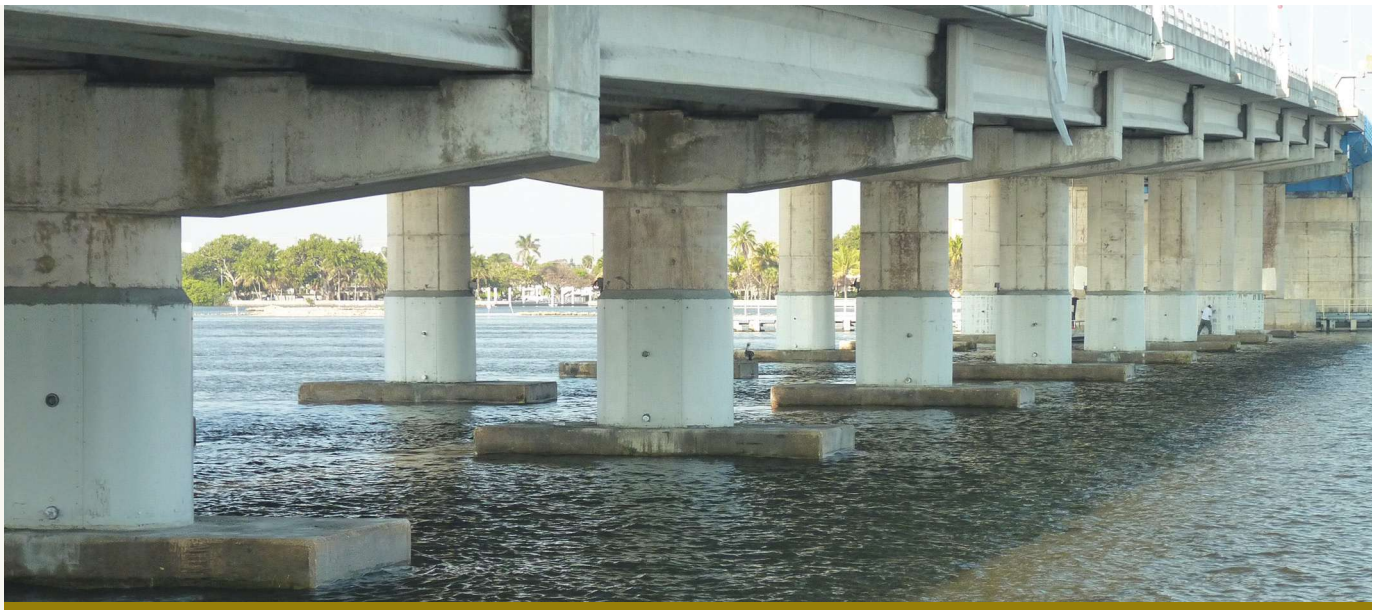


Figure 5. Installed dry jacket system that includes galvanic jackets with activated anodes (no bulk anodes).

Figure 6. Dry jacket that includes alkali-activated anodes on the pile prior to jacketing (bulk zinc anode not shown).

jacket with activated anodes is necessary but bulk zinc anodes are not required.

Alkali-activated distributed anodes are used in both wet conditions (including saltwater, brackish, and freshwater), and dry conditions. If the jacket is installed with the bottom of the form below low tide, then a submerged bulk zinc anode (BA) is used in addition to the alkali-activated anode in the jacketed area.

Galvanic jackets with alkali-activated distributed anodes are flexible in design. The anode size and spacing can be adjusted based on the desired service life. The anodes can be installed directly onto the pile or attached to stay-in-place formwork (Fig. 6). The anodes are used with a variety of formwork including removable concrete forms, stay-in-place FRP, or modular PVC forming systems that are assembled in the field (Fig. 7).

Figure 7. Self-activated anodes inside modular PVC formwork.

Conclusion

Galvanic jackets are a durable, low-maintenance cathodic protection solution to mitigate pile corrosion and can provide an estimated service life in the range of 20 to 50+ years without the need for external power or monitoring. To ensure the highest quality installation, galvanic jackets should be designed, inspected, and energized by a cathodic protection specialist experienced with concrete structures.

J. Christopher Ball is president of Vector Corrosion Services in Wesley Chapel, Fla.

References

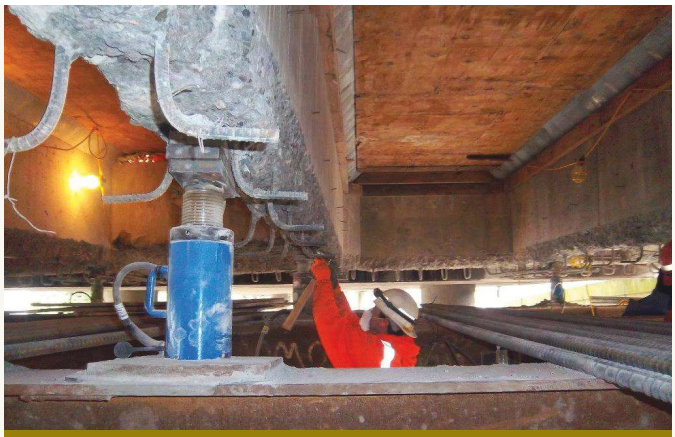
1. Hartt, W. H. and M. Rapa. 1998. *Condition Assessment of Jackets Upon Pilings for Florida Bridge Substructures*. Final Report, WPI No. 0510803. Florida Department of Transportation, Tallahassee, FL.

2. Clemeña, G. C., and D. R. Jackson. 1999. *Evaluation of Anodes for Galvanic Cathodic Prevention of Steel Corrosion in Prestressed Concrete Piles in Marine Environments in Virginia*. VTRC 00-R3. Virginia Transportation Research Council, Charlottesville, VA.

3. Hartt, W. H., C. C. Kumria, and R. J. Kessler. 1993. "Influence of Potential, Chlorides, pH, and Precharging Time of Embrittlement of Cathodically Polarized Prestressing Steel." *Corrosion*, NACE International, Houston, TX. Vol. 49, No. 5 (May), pp. 377-385.

CONCRETE BRIDGE PRESERVATION

CBP



Box girder is temporarily supported after the deteriorated bottom slab was removed. Photo: Washington State Department of Transportation.

In-Service Replacement of a Reinforced Concrete, Box-Girder Bottom Slab

by Craig R. Boone, Washington State Department of Transportation

With an aging infrastructure and limited funding, engineers are being called upon to find practical solutions to transportation issues. One recent example is a bridge repair that was completed by the Washington State Department of Transportation (WSDOT). The repair consisted of removing and replacing the bottom slab of a reinforced concrete box girder while maintaining traffic on the bridge deck. The successful completion of this repair saved millions of dollars in construction and user costs, and minimized disruptions to the nearly 25,000 vehicles that use the bridge every day.

In recent years, WSDOT bridge inspectors were finding significant deterioration in the bottom slab of span 11 of Bridge 5/537S. The bottom slab had large areas of spalling with exposed rusty reinforcement. The concrete had a powdery consistency, and was easily removed for its full depth. Because of this, the bridge was classified as structurally deficient. WSDOT considered removing and replacing the span, but recognized the bridge would be out of service for months. Fortunately, the space below the bridge was vacant, which meant there was an opportunity to temporarily support the existing structure. With a strong desire to maintain traffic on the bridge, and recognizing that other elements of the bridge were still in good condition, WSDOT decided to remove and replace the bottom slab while temporarily supporting the span. The temporary support system was designed such that traffic could be maintained on the bridge deck.

Design of the repair included several unique challenges, the first of which was how to temporarily support the span in a way that would allow the bottom slab to be removed and replaced. Small holes were created in the bottom slab so jacks could be inserted to support the webs, just above the bottom slab. Because the positive moment reinforcing steel was to be removed, jacks had to be closely spaced at 7 ft 6 in. on center along the length of the span to provide nearly continuous support (54 jacks total).

A second challenge was the design of the interface between the existing webs and the new bottom slab. Details were developed with a focus on ensuring good concrete consolidation and no air pockets. Also, shear keys were chipped into the bottom of the existing webs to ensure composite behavior between the new and existing concrete.

A third challenge resulted from providing access hatches to each cell. The access hatches meant less room for new positive-moment reinforcing steel. The original capacity of the bridge was restored using smaller, higher-strength reinforcing bars that were placed in bundles between the hatches.

Traffic was maintained on the bridge for the duration of the repair, with the exception of 2 days when the concrete was placed and allowed to gain a strength of 2 ksi. The temporary support system was left in place for 28 days following the concrete placement. The total time to construct the repair was 3 months, and the total cost to design and construct the repair was approximately $1 million.

Craig R. Boone is a bridge asset engineer with the Washington State Department of Transportation in Tumwater, Wash.

Pairing Prefabricated Bridge Elements with UHPC Connections

by Dr. Benjamin A. Graybeal, Federal Highway Administration

Owners across the United States and Canada are recognizing the value pairing ultra-high-performance concrete (UHPC) connections technology and prefabricated bridge elements to build robust structures. Structural connections must perform at least as well as the connected elements, but traditional field-cast connections have at times proved to be difficult to fabricate, difficult to install, expensive, and susceptible to underperformance. The exceptional mechanical and durability properties of UHPC open doors to field-cast connections that simplify construction while simultaneously delivering a structure anticipated to meet long service life demands.

Advances in concrete technology, including fiber reinforcement, superplasticizers, particle packing, and supplementary cementitious materials, began to be packaged together into a new generation of cementitious composite materials in the 1970s and 1980s. Commercialization in the 1990s brought to market a new class of materials referred to as UHPC. Available today primarily from major construction materials suppliers, but also likely available soon as a locally sourced product, UHPC is gaining widespread attention in American and Canadian markets as a field-cast grout. Market conditions and owner expectations in other parts of the world are creating alternative focal points, such as using prefabricated UHPC components for curtain walls and façades, pedestrian bridges, urban furniture, and even security applications.

Deployment of UHPC Connections

Deployments of UHPC connections have shown significant growth in recent years, with more than 130 bridges already in service. The first bridges to engage this concept were constructed in Ontario starting in 2005, and in New York State starting in 2009 (Fig. 1 and see *ASPIRE*™ Fall 2009). Dozens of new deployments are happening each year, with experienced owners moving to institutionalize the technology and new owners encouraging first installations. As shown in Fig. 2, the early adopters have continued to press forward with use of this technology as the broader community comes on board.

The robustness of the UHPC connections has resulted in a few high profile deployments wherein owner-defined requirements stipulated that the overall finished structure needed to have an exceptionally long service life. Two ongoing examples include the redecking of the 3.5-mile-long Pulaski Skyway in Newark, N.J., and the construction of the Nipigon River Bridge by the Ontario Ministry of Transportation on the Trans-Canada Highway. Two upcoming examples are the rehabilitation of the Franklin Avenue Bridge over the Mississippi River in Minneapolis, Minn., and the Major Deegan Expressway in New York City.

FHWA Every Day Counts Support

The Federal Highway Administration's (FHWA's) Every Day Counts (EDC) program, now in its sixth year, is geared toward advancing effective, proven, market-ready technologies into widespread use. FHWA's Turner-Fairbank Highway Research Center began investigating the use of UHPC in 2001, leading to the eventual development and delivery of optimal solutions that are in use today. Given the level of market adoption in 2014, it was decided to include UHPC connections as one of the 11 technologies whose deployment is being supported via EDC in 2015 and 2016.

Figure 1. Ultra-high-performance concrete connections were used in the bridge over the Canandaigua Outlet in New York. Photo: Federal Highway Administration.

The EDC program provides stakeholders with the assistance they need to successfully demonstrate, integrate, and institutionalize a technology into their toolbox of solutions. For UHPC connections, the deployment support team is delivering workshops across the country, is facilitating site visits to ongoing projects, is supplying expert technical assistance, and is delivering the support content (for example, design and construction guidance) needed by the adopting entity. Admittedly, the strong interest in UHPC connections technology has stretched the capacity of the deployment team, but the team is looking forward to continuing to meet stakeholder needs throughout 2016 and beyond.

Fundamental Principles

The fundamental mechanical principle undergirding the performance of UHPC connections is the fact that increasing the tensile resistance of concrete will allow it to better engage the connectors originating from a prefabricated concrete element. The tensile splitting and pullout behaviors that commonly limit the capacity of field-cast cementitious connections are mitigated

Figure 2. Locations of ultra-high-performance concrete connections currently in-service across the United States and Canada. Figure: Federal Highway Administration, created using Google Maps.

through the combination of the high load of fiber reinforcement and the cementitious matrix of the UHPC. In effect, UHPC acts as liquid confinement around reinforcement and other connecting elements in order to allow for simple, small connections that exceed the capacity of the adjacent prefabricated components. UHPC affords a pre- and post-cracking sustained tensile strength greater than 720 psi (5 MPa), as shown in the tensile responses for a set of example UHPCs in Fig. 3.

Common Connections

The most common connection is a reinforcing bar lap splice arrangement. Used today to connect prefabricated concrete bridge deck panels, the top flanges of decked girders, the backwalls of prefabricated integral abutment elements, and even pier columns to caps, these connections have proved to be cost effective to fabricate and easy to assemble in the field. The research-based design guidance indicates that uncoated and epoxy-coated reinforcement can be developed beyond the bar yield strength when the embedment length is only eight times the bar diameter. This results in non-contact lap spliced connections for No. 5 bars that might only be 6 in. wide and will not require post-tensioning, headed bars, hooked bars, lacer bars, or any other specialized anchorages.

UHPC also affords exceptional interface bond to precast concrete, increasing the likelihood that a leak-free structure can be placed into service. The enhanced bond is attributed to the fineness of the UHPC matrix combined with the increased tensile strength; however, the bond strength will only be increased if the surface of the precast concrete element is appropriately prepared. Most commonly, this preparation includes the creation of micro- and macrotexture through the use of a paste retarder to create an exposed aggregate surface along with prewetting to reduce the desiccation of the field-cast UHPC adjacent to the interface.

Field-cast UHPC can also be used for shear connections between bridge decks and supporting girders, for headers at expansion joints, for link slabs over piers in multi-span structures, and for seismic retrofits of substandard lap splices in conventional reinforced concrete substructures. Emerging uses of field-cast UHPC include its use as a structural overlay for rehabilitating bridge decks and as a field-cast retrofit to increase the capacity of deteriorated steel beam end regions.

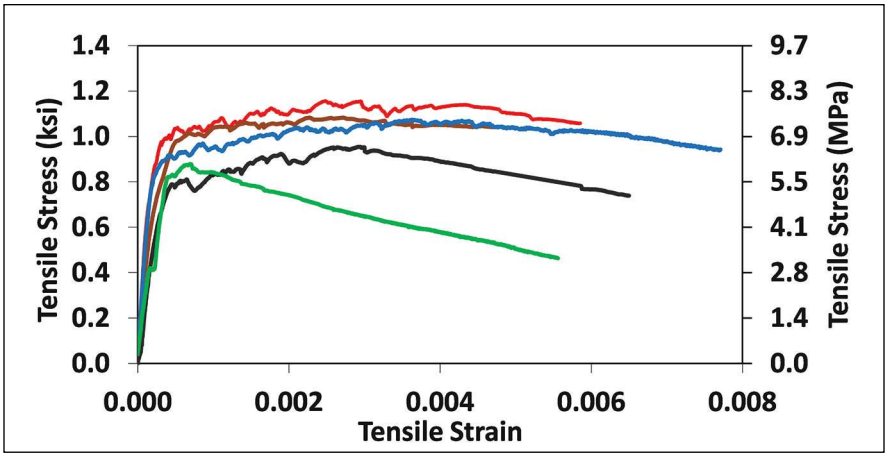


Figure 3. Tensile stress-strain response of five different ultra-high-performance concretes. Figure: Federal Highway Administration.

Conclusion

UHPC is rapidly being adopted as a field-cast material that addresses long-standing bridge construction needs and that outperforms conventional solutions. Fourteen states and four Canadian provinces have already begun using this technology, and use is expected to continue to grow over the coming years as it becomes a common state-of-the-practice solution. The bridge community is yet again demonstrating that proven solutions addressing critical need will be vetted and implemented in ways that deliver enhanced performance for future generations of the traveling public.

EDITOR'S NOTE

Please see the announcement in the last issue of ASPIRE *for The First International Interactive Symposium on UHPC being held on July 18-20, 2016. See www.uhpc2016.com for another avenue to learn more about the application of this material.*

For More Information

FHWA's UHPC research and innovation efforts are led by the author at the Turner-Fairbank Highway Research Center. Further information on UHPC technology can be obtained by accessing the FHWA UHPC webpage (https://www.fhwa.dot.gov/research/resources/uhpc/) or by contacting the author at benjamin.graybeal@dot.gov.

Crystalline Silica Exposure in the Workplace

The Occupational Safety and Health Administration's ruling likely will materially change practices in the concrete and construction industries

by John S. Dick, J. Dick Precast Concrete Consultant LLC

ASPIRE™ rarely ventures into health and safety issues involving concrete manufacturing or jobsite construction. However, a ruling published by OSHA in the Federal Register on March 25, 2016, requires rapt attention by every company engaged in ready-mixed or precast concrete production and conducting operations on concrete and certain other materials on jobsites. Construction engineers, agency personnel, and consultants will experience new procedures and restrictions on jobsites. This action by OSHA will impact normal operations of a long list of different kinds of businesses and industries. This article focuses on the ruling and its implications to both manufacturing and construction activities related to concrete bridges.

Abbreviations Used in this Article

- $\mu g/m^3$ – micrograms of silica per cubic meter of air
- AL – action level (25 $\mu g/m^3$ averaged over an 8-hour day)
- APF – assigned protection factor
- COPD – chronic obstructive pulmonary disease
- CT – computed tomography (CAT scan)
- HEPA – high-efficiency particulate air—an air filter that is at least 99.97% efficient in removing particles 0.3 microns (0.001 mm) or larger in diameter
- HRCT – high-resolution computed tomography
- OSHA – Occupational Safety and Health Administration
- PEL – permissible exposure limit (50 $\mu g/m^3$ averaged over an 8-hour day)
- PLHCP – physician or other licensed health care professional
- PPE – personal protective equipment
- RCS – respirable crystalline silica
- SSN – social security number

Background

Crystalline silica is one of the most common minerals on earth. It is found in sand, stone, concrete, brick, block, and mortar. "Respirable" silica consists of very small particles capable of reaching the lungs, less than 10 microns in aerodynamic diameter—hundreds of times smaller than "sand." Prolonged exposure has been shown to sometimes lead to silicosis, COPD, lung cancer, and kidney disease.

Prior to this ruling, the applicable standards for exposure were established in 1971, when OSHA was created. The government claims that this standard does not adequately protect workers. The government website documents show the projected numbers of affected workers, cost savings, and benefits to workers related to the new ruling. The new rule PEL is roughly 50% of the previous PEL for general industry and roughly 20% of the previous PEL for the construction industry.

The two new crystalline silica rules are: 29 CFR 1910.1053 pertaining to general industry (for example, precast concrete manufacture) and maritime and 29 CFR 1926.1153 that pertains to construction. The effective date of this ruling is June 23, 2016. The mandatory dates for compliance are given at the end of this article. These regulations and additional information may be obtained at www.osha.gov/silica.

Effects on Operations

The means of compliance for construction and manufacturing are slightly different but many are the same. The differences are that construction practices are intermittent, occurring at indiscriminate locations, while plant operations are usually repetitious and in more determinant locations. The standards are intended to provide equivalent protection for all workers while accounting for the different work activities, anticipated exposures, and other conditions in these sectors.

There are numerous specific details that pertain to many of the requirements. This article is not all inclusive. The regulations should be consulted.

In general, the standards contain the AL, the PEL, and other requirements including:

- employee exposure assessment,
- regulated areas,
- methods of compliance,
- respiratory protection,
- medical surveillance,
- communication of silica hazards to employees, and
- recordkeeping.

For ease of understanding, the ruling on construction (1926.1153) is taken up first. Any differences will be explained. The construction standard includes a lengthy "Table 1—Specified Exposure Control Methods When Working With Materials

Containing Crystalline Silica." The table lists 58 different "Equipment and Tasks" with "Engineering and Work Practice Control Methods" for each and the "Required Respiratory Protection and Minimum APF" for each. The APF refers to OSHA's respiratory standard for general industry (29 CFR 1910.134) that defines the required level of employee protection, which must be complied with when employees are required to use respirators for protection against crystalline silica exposure. The table differentiates the APF by 4 hours or less of exposure per shift and more than 4 hours of exposure. For construction, it is assumed that for all tasks in Table 1, employees are exposed at or above the AL, and for all operations that requires a respirator, the employee is exposed above the PEL. Employers with approved compliance with Table 1 are not required to measure workers' exposure and are not subject to the PEL. Rather than complying with Table 1, workers' exposure may be measured to determine dust control strategies.

Employers must implement "written exposure control plans" for all tasks that involve exposure. The standard for construction also includes a provision for a competent person (that is, a designated individual who is capable of identifying crystalline silica hazards on the jobsite and who possesses the authority to take corrective measures to address them) to implement the written exposure control plan.

For industry, employers must measure the amount of RCS if it "may" be at or above the AL. Workers must be protected for exposures above the PEL.

The industry standard does not apply if the task is indistinguishable from one listed in Table 1 and will be repeated regularly in the same environment and in the same conditions.

Mitigation

The objective of the standards is to limit exposures to or below the PEL. The employer must use "engineering controls and work practices" first to accomplish this. A respirator must be used only after all feasible engineering and work practice controls have been implemented.

For processes that generate RCS above the PEL, regulated areas must be established separate from other work areas. Boundaries must be demarcated to limit access. Warning signs are required.

A significant level of demarcation is whether employees are exposed above the PEL for 30 or more days per year. For exposures of less than 30 days, engineering controls need not be used but respiratory protection is required.

Engineering and Work Practice Controls

These controls include the design and implementation of new tools, crafting processes, and methods to control RCS. There are four categories of control:

1. Substitution—replace materials containing silica with those that do not.
2. Isolation—employ an enclosure, for example, a physical barrier to isolate the silica dust. Equipment cabs must be sealed. Dust contained within an enclosure must be captured and disposed of properly.
3. Ventilation—capture the contaminant at or near the source or dilute the contaminant with large quantities of air.
4. Suppression—one of three systems can be applied to many different operations such as material handling, rock crushing, abrasive blasting, and operation of heavy equipment:
   a. Wet dust suppression, in which a liquid or foam is applied to the surface of the dust-generating material
   b. Airborne capture, in which moisture is dispensed into a dust cloud, collides with particles, and causes them to drop from the air
   c. Stabilization, which holds down dust particles by physical or chemical means (lignosulfonate, calcium chloride, and magnesium chloride are examples of stabilizers)

Accumulations of Silica

Accumulations must be cleaned by HEPA filtering or wet methods. Water contaminated with RCS must be cleaned before it dries since the residue might contribute to exposure. Dry sweeping or brushing is not permitted unless wet sweeping, HEPA-filtered vacuuming, or other methods are not feasible.

Use of Respirators

Respirators are required in four situations:

1. Periods necessary to install or implement feasible engineering and work practice controls
2. Work operations such as maintenance and repair activities where meeting the PEL with engineering and work practice controls is not feasible
3. Work operations where all feasible engineering and work practice controls have been implemented but do not reduce exposures to the PEL (examples include some tuckpointing and abrasive blasting operations)
4. In a regulated area, or, for construction, during periods when the employee is in an area where respirator use is required under Table 1. Also, respiratory protection is required for tasks not listed in Table 1.

Sources of RCS

Manufacturing Plant and Jobsite

- *Operations on hardened concrete*
  - *Abrasive blasting*
  - *Chipping, grinding, drilling, polishing, rubbing, and patching*
- *General operations*
  - *Operating wheeled equipment*
  - *Working near traveled lanes and roadways*
  - *Dumping and conveying aggregates*
  - *Handling cements and supplementary cementitious materials*
  - *Cleaning concrete trucks or placement machinery*
  - *Wind-blown dust*
  - *Screening patching sand*

Medical Surveillance

For construction, surveillance must be made available to employees who are required by the standard to use respirators for 30 days or more per year. For industry, surveillance is required for employees exposed at or above the AL for 30 days or more per year. The employer must bear the cost of the examination, travel, and time away. Exams must be performed by a PLHCP. A baseline medical exam must be made within 30 days of the initial assignment. The exam must include the following:

- Medical and work history; history of respiratory system dysfunction
- Physical examination with special emphasis on the respiratory system
- Chest X-ray or an equivalent diagnostic study such as a digital

chest radiograph or CT or HRCT scans
- Pulmonary function test
- Testing for latent tuberculosis infection

The employer will receive only the following information unless the employee provides written authority:

- Date of the examination
- Statement that the examination has met the requirements of this rule
- Any limitations on the employee's use of respirators

There are numerous additional details concerning medical surveillance. They may be found in the written rule.

Communication of the Hazards

The standard includes a cross-reference to OSHA's Hazard Communication Standard (29 CFR 1910.1200). It requires the following that are not new:

- Include RCS in the hazard communication program
- Implementation must include labels, material safety data sheets, and information and training
- Ensure access to labels on containers of respirable crystalline silica and material safety data sheets
- Provide access to copies of the standard without cost to employees
- Address at least the hazards of cancer, lung effects, immune system effects, and kidney effects

Training

Training must be conducted in accordance with the standards, tailored to operations at the work site, information on health impacts associated with silica exposure, and must include at least the following:

- Operations that could result in exposures exceeding the PEL
- Principles of safe handling of silica materials
- Methods used to minimize exposure
- Specific procedures implemented to protect employees from exposure, including appropriate work practices and use of PPE such as respirators and protective clothing
- Description of the medical surveillance program
- Demonstrable knowledge of these components of training through discussion, written tests, or oral quizzes

Recordkeeping

The extent of employer records required to be compiled and maintained may be onerous. These records include: air monitoring, objective data, and medical surveillance. The first two are considered employee exposure records and all must be maintained for the duration of employment plus 30 years (in compliance with 29 CFR 1910.1020).

For records of exposure measurements, required records include: date of sample; identification of operation of exposure; sampling and analytical method; number, duration, and results of samples; identity of laboratory; type of PPE used; name, SSN, and job classification of employees.

Records for employees covered by medical surveillance include: name and SSN; written opinion of PHLCP; copy of information furnished to PLHCP.

Dates of Compliance

For construction, all obligations for compliance start June 23, 2017, except certain requirements for laboratory analysis start on June 23, 2018.

In industry, employer obligations to comply begin June 23, 2018. This time period following the effective date this year is designed to allow for initial exposure assessments, establish regulated areas, provide initial medical examinations, and comply with other provisions.

Engineering controls need to be in place by June 23, 2018. This is to allow affected employers sufficient time to design, obtain, and install the necessary control equipment. Early indications are that equipment and tool manufacturers will design new products that will help eliminate or reduce RCS and assist with disposal. During the period before engineering controls are implemented, employers must provide prescribed respiratory protection to employees.

Medical surveillance starts June 23, 2018, for employees exposed above the PEL and June 23, 2020, for employees exposed at or above the AL.

Industry Support

It is expected that industry groups and affected ancillary businesses will begin to offer help to individual manufacturers and contractors. For construction, the contractor associations should be consulted. A web search has also yielded relevant information provided by major industrial insurers.

John S. Dick—formerly director of certification programs and director of transportation systems at PCI—is now a consultant residing in Colorado.

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.wsdot.wa.gov/publications/manuals/fulltext/M22-01/design.pdf
This is a link to the *WSDOT Design Manual*, that includes Chapter 950 Public Art, which was mentioned in the Perspective article on page 10.

http://www.spokanearts.org/murals/
This is a link to the Murals website for Spokane Arts in Spokane, Wash., that was mentioned in the Perspective article on page 10. Several mural examples are shown.

http://www.dot.state.mn.us/dresbachbridge/
This is a link to the Minnesota DOT project website for the Dresbach Bridge that was the topic of the Project Profile article on page 14.

http://www.wsdot.wa.gov/Projects/SR162/PuyallupRiverBridge/default.htm
This is a link to the WSDOT project webpage for the Puyallup River Bridge that was the topic of the Project Profile article on page 18. The webpage has a link for information on the unique concrete truss that the new bridge replaced.

http://www.cement.org/top-resources/pca-centennial
This is a link to the Centennial Celebration webpage for the Portland Cement Association, which is mentioned in the article on page 22. The webpage includes a link to a 15-minute video "One Hundred Years of PCA."

https://www.fhwa.dot.gov/publications/research/infrastructure/structures/hpc/13060/13060.pdf
This is a link to an FHWA report by Russell and Graybeal "Ultra-High Performance Concrete: A State-of-the Art Report for the Bridge Community," that was cited as a reference in the article on page 46.

http://www.fhwa.dot.gov/publications/research/infrastructure/structures/14084/14084.pdf
This is a link to an FHWA TechNote by Graybeal "Design and Construction of Field-Cast UHPC Connections," that was cited as a reference in the article on page 36.

http://www.fhwa.dot.gov/research/resources/uhpc/publications.cfm
This is a link to a webpage with links to publications produced by FHWA's research and development program on the performance and use of ultra-high performance concrete (UHPC), which was mentioned in both the Concrete Bridge Technology article on page 36 and the FHWA article on page 46.

http://www.fhwa.dot.gov/innovation/everydaycounts/edc-3/uhpc.cfm
This is a link to FHWA's Every Day Counts 3 (EDC-3) website for UHPC Connections for Prefabricated Bridge Elements that is the topic of the FHWA article on page 46.

https://www.oregon.gov/ODOT/HWY/BRIDGE/docs/BDDM/apr-2015_finals/sec_1_apr2015.pdf
This is a link to the Oregon DOT *Bridge Design and Detailing Manual*. Article 1.5.5.1.17 High Strength Reinforcement provides design guidance on the use of high-strength reinforcement that was discussed in the Concrete Bridge Technology article on page 28.

https://www.fhwa.dot.gov/bridge/concrete/hif15016.pdf
This is a link for a no cost download of FHWA's *Post-Tensioned Box Girder Design Manual* that is discussed in the Concrete Bridge Technology article on page 40.

http://www.cptechcenter.org/events/archive/IL_Tollway_docs/Tab%204%20Specifications/10%20Spec-Performance%20Spec%20for%20HPC-Superstructure.pdf
This is a link to the Illinois Tollway's crack-resistant high-performance concrete special provisions that are on the National Concrete Pavement Technology Center website. These special provisions were mentioned in the Concrete Bridge Technology article on page 32.

http://www.illinoistollway.com/documents/10157/90097/High-Performance+Concrete+for+Bridge+Decks-Final+Report.pdf
This is a link to the CTLGroup report that provided the research basis for the Illinois Tollway's crack-resistant high performance concrete special provision that were mentioned in the Concrete Bridge Technology article on page 32.

Bridge Technology

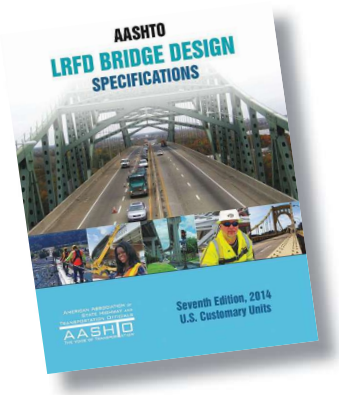
NEW **www.fhwa.dot.gov/pavement/concrete/pubs/hif16001.pdf**
This is a link to an FHWA TechBrief "Supplementary Cementitious Materials—Best Practices for Concrete Pavements." While the document is directed toward concrete pavements, it has useful information that is applicable to bridge construction as well.

NEW **http://1121.sydneyplus.com/PCA/Portal/default.aspx?lang=en-US**
This is a link to PCA's Online Library Catalog which now provides free access to more than 2000 PCA publications including more than 2000 archival PCA technical reports, promotional literature, engineering bulletins, and information sheets. These PCA publications are fully searchable and full-text downloadable. More historical PCA publications will be added to the Library catalog for full-text online access as they are digitized.

NEW **http://learning.crsi.org/products/crsi-timesaving-design-aids-3-webinar-package**
This is a link to the three-part Concrete Reinforcing Steel Institute webinar series "Timesaving Design Aids for Reinforced Concrete" that provides design professionals with many ways to reduce the time is takes to design and detail conventionally reinforced concrete members while still complying with the provisions of the 2104 edition of ACI 318, Building Code Requirements for Structural Concrete.

The AASHTO LRFD Bridge Design Specifications: Torsional Resistance

by Dr. Dennis R. Mertz



Beam regions (B-regions), where it is appropriate to assume that plane sections remain plane after loading, may be designed for shear and torsion using either the sectional modified compression-field theory (MCFT) resistance model or the strut-and-tie method (STM). Disturbed regions (D-regions) where the plane-sections-remain-plane assumption of flexural theory is not valid should be designed for shear and torsion using the STM.

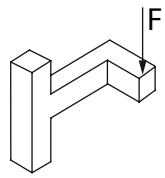
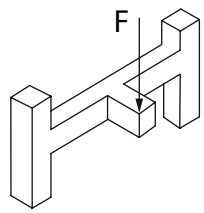
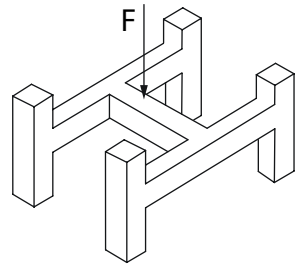
B-region theory assumes that the resistance at a particular section depends only on the calculated values of the sectional force effects—that is, moment, shear, axial load, and torsion—and does not consider the specific details of how the force effects are introduced into the member. The STM recognizes the significance of how the loads are introduced into a D-region and how that region is supported. It is applicable to both B- and D-regions, but it is not practical to apply the STM to B-regions.

As the STM used for D-regions proportions and details members without an explicit treatment of moment, shear, torsion or thrust, it will not be discussed further herein. (See my column in the Winter 2011 issue of *ASPIRE*™.)

Sections that are designed for live loads using the distribution-factor methods for beam-slab bridges are not typically investigated for torsion.

Torsion is often categorized as either compatibility or equilibrium torsion as illustrated in Table 1. Equilibrium torsion is required for stable equilibrium by the topology of the structure and must be addressed in the design. All torsion in a statically determinant structure is equilibrium torsion. Torsion in a statically indeterminate structure may be either compatibility or equilibrium torsion. Torsion that results from rotational restraint, but which is not required to keep the applied loads in stable equilibrium because other load paths exist to support the loads, is called compatibility torsion. It is not necessary to design for compatibility torsion as long as the other load paths are properly designed for the redistributed forces. Consideration should be given to aesthetic issues that arise from cracking associated with not designing for compatibility torsion.

Table 1. Categorization of torsion. Note: N/A = not applicable. Figure: Dennis Mertz.

Structural Determinacy	Torsion Category	
	Equilibrium	Compatibility
Statically Determinate		N/A
Statically Indeterminate		

Thus, in a statically indeterminate structure where significant reduction of torsional moment in a member can occur due to redistribution of internal forces upon cracking, the applied factored torsional moment at a section T_u may be reduced to ϕT_{cr} provided that moments and forces in the member and adjoining members are adjusted to account for the redistribution.

If the factored torsional moment T_u is less than or equal to 25% of the factored pure torsional cracking moment, only a very small reduction in shear capacity or flexural capacity will occur and, hence, can be neglected. Further, equations for the torsional cracking moment for solid and hollow sections are specified.

The nominal torsional resistance is taken as:

$$T_n = \frac{2A_0 A_t f_y \cot\theta}{s}$$

with the familiar variables used for shear resistance with the addition of A_0, the area enclosed by the shear-flow path.

The topic of combined shear and torsion will be discussed in a future column.