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THE CONCRETE BRIDGE MAGAZINE

FALL 2018

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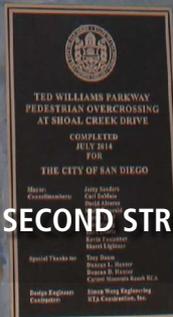
## Ted Williams Parkway Pedestrian Overcrossing *San Diego, California*

**ST. CROIX RIVER CROSSING**  
*Oak Park Heights, Minnesota, and St. Joseph, Wisconsin*

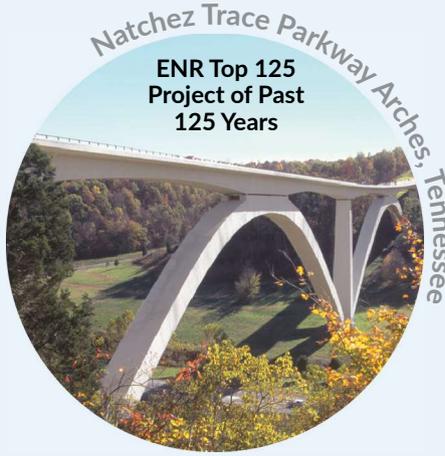
**35TH STREET PEDESTRIAN BRIDGE**  
*Chicago, Illinois*

**PURPLE HEART MEMORIAL BRIDGE**  
*Beaumont, Texas*

**SECOND STREET BRIDGE OVER THREE-MILE CREEK**  
*Leavenworth, Kansas*

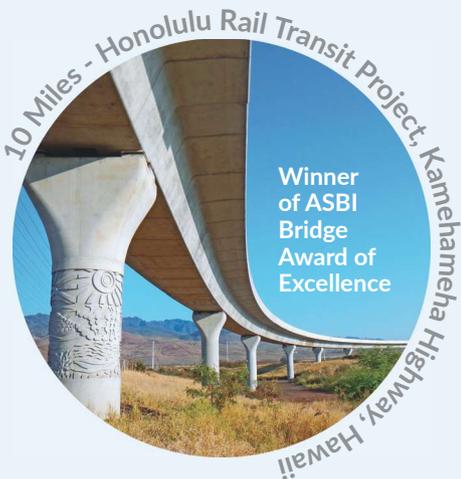


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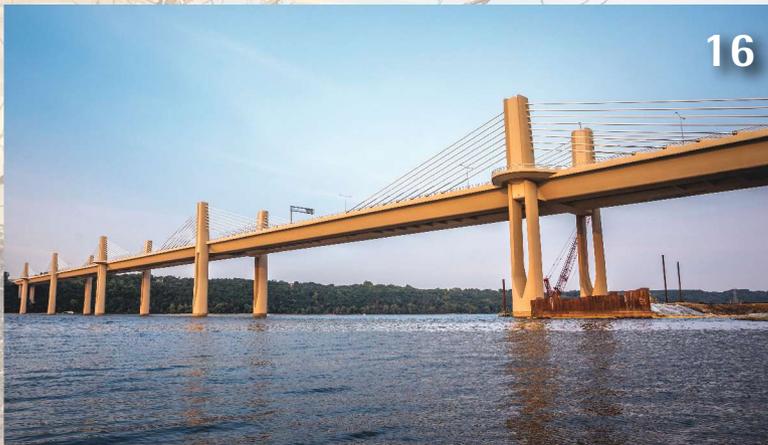
*Through the last forty years, FIGG bridges have stood strong through the worst hurricanes; provided timeless beauty; and created sustainable, low-maintenance concrete connections for communities.*





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Photo: Dave Burk Photography.



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Photo: HDR.



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Photo: Texas Department of Transportation Beaumont District.

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Photo: TranSystems/City of Leavenworth.

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Photo: PCI

# Concrete Technologies Are Not Standing Still: Let's Ensure Any Changes Are Improvements

William N. Nickas, *Editor-in-Chief*

Recently, at the midyear meeting of the American Association of State Highway and Transportation Officials (AASHTO) Technical Committee on Concrete (T-10), someone asked me which changes in the bridge industry have me most excited. That is a tough question.

Concrete technologies are not standing still. Early adopters are trying out the newest admixtures that may enhance concrete placement, densify the concrete, or increase its strength. Researchers, owners, and contractors are also exploring the use of fibers that change the structural behavior of concrete. Combining these sorts of innovative materials with traditional ones, and with some new strand and reinforcing bar technologies, will likely increase the service life of newly constructed structures.

Today, there is an urgent need to improve our productivity. When comparing staff hours per unit of solution or service provided, industries such as agriculture, manufacturing, and logistics have far outpaced construction. Clearly, there is a business case to be made for new tools and technological changes that will help construction concrete staff work more efficiently and improve the infrastructure of the concrete bridge sector of the economy.

One exciting area of innovation is artificial intelligence (AI). Rebar-tying machines and three-dimensional printing are already applying AI. These new technologies show that AI does have place in our bridge construction and operating world—we just have to figure out what its role will be and where AI fits best in our work processes.

We also have to make sure that those who will work in our industry are educated and trained appropriately to apply logic and good judgment in their work decisions, particularly as they encounter new technologies, new tools, and new ideas. Today, our newest workforce members have access to lots of data, but they may not be able to make sense out of

all the information. As we equip our workforce, our challenge is to communicate the right information and at the right time. To upgrade our bridge construction workforce, we must take full advantage of information technology. For example, a project control system using Bridge Information Modeling gives everyone working on a project the opportunity to sequence the information to match the workflow and systematically retrieve data for decades to come.

**As we equip our workforce, our challenge is to communicate the right information and at the right time.**

I firmly believe our bridge community should always evaluate the possible advantages and risks involved in technological changes in the context of predetermined goals toward improvement. The newest materials that are becoming available for improving concrete structural performance offer a tremendous opportunity to simplify many details, but new technologies may require rethinking some structural tenets such as phi factors, redundancy, or ductility. We must understand how the newest details and materials work, and what costs and risks are associated with their use.

In a perspective published in the Summer 2014 issue of *ASPIRE*<sup>®</sup>, Dr. Ben Greybeal predicted that certain “transformational innovations” would dramatically improve concrete construction in the near future. I can see now that his envisioned future is coming true. Thank you for your readership and the opportunity to showcase concrete bridge solutions. In 2019, *ASPIRE* will continue to share the news of our industry and help you understand the latest standards, technologies, and trends that affect us all. 

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



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## CONCRETE CALENDAR 2018–2019

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

**October 10–13, 2018**

### **PCI Committee Days and Membership Conference**

Loews Chicago O'Hare Hotel  
Rosemont, Ill.

**October 14–18, 2018**

### **ACI Fall 2018 Convention and Exposition**

Rio All-Suites Hotel and Casino  
Las Vegas, Nev.

**October 15, 2018**

### **Deadline for submitting abstracts for the Second International Interactive Symposium on Ultra-High-Performance Concrete**

To be held June 2–5, 2019, at the Hilton Albany, Albany, N.Y.

**October 22–25, 2018**

### **PCA Design and Control of Concrete Mixtures: The Course**

PCA Campus  
Skokie, Ill.

**October 24–26, 2018**

### **PTI Level 1 & 2 Bonded PT Field Specialist Training and Certification**

Tallahassee, Fla.

**November 6–7, 2018**

### **ASBI 29th Annual Convention**

Loews Chicago O'Hare Hotel  
Rosemont, Ill.

**November 14–16, 2018**

### **PTI Level 1 & 2 Bonded PT Field Specialist Training and Certification**

Austin, Tex.

**December 5–7, 2018**

### **PTI Level 1 & 2 Bonded PT Field Specialist Training and Certification**

Seattle, Wash.

**December 31, 2018**

### **Deadline for submitting PTI Project Awards for the 2019 PTI Convention**

To be held May 5–8, 2019, in Seattle, Wash.

**January 13–17, 2019**

### **Transportation Research Board 98th Annual Meeting**

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

**January 18, 2019**

### **Deadline for submitting abstracts for the 2019 International Accelerated Bridge Construction Conference**

To be held December 11–13, 2019, in Miami, Fla.

**January 21–25, 2019**

### **World of Concrete 2019**

Las Vegas Convention Center  
Las Vegas, Nev.

**February 26–March 2, 2019**

### **PCI Convention**

Kentucky International Convention Center  
Louisville, Ky.

**March 24–28, 2019**

### **ACI Spring 2019 Conference**

Quebec City Convention Centre and Hilton Quebec  
Quebec City, Canada

**April 8, 2019**

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

J.J. Pickle Research Campus  
Austin, Tex.

**April 8–10, 2019**

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

Duke Energy Convention Center  
Cincinnati, Ohio

**June 2–5, 2019**

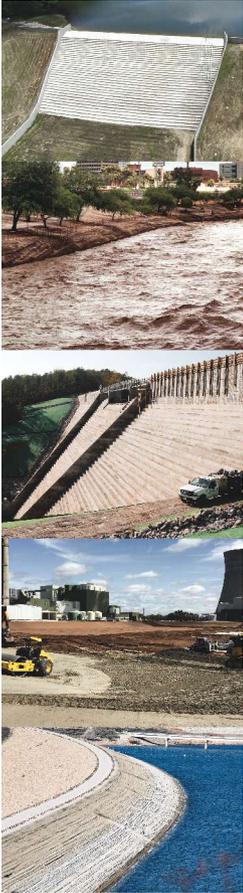
### **Second International Interactive Symposium on Ultra-High-Performance Concrete**

Hilton Albany  
Albany, N.Y.

**June 10–13, 2019**

### **International Bridge Conference**

Gaylord National Resort and Convention Center  
National Harbor, Md.



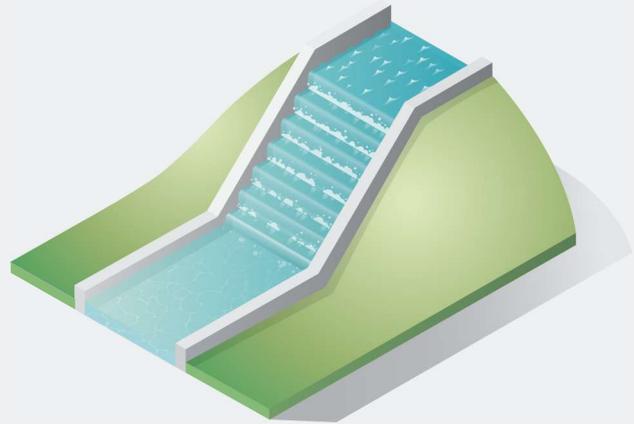
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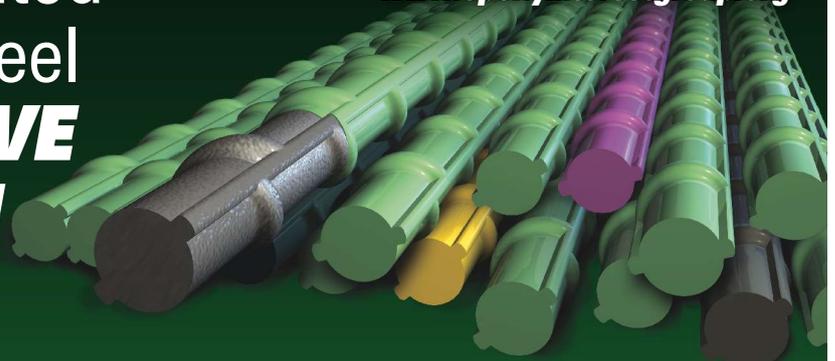


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# Designing for the Real World

Kleinfelder focuses on ensuring that its designs meet every stakeholder's needs while offering efficient constructability

by Craig A. Shutt

Kleinfelder's combination of engineers, scientists, and construction professionals has provided infrastructure solutions to clients since 1961. The company, which has grown in size and geographic range through a series of acquisitions and expansions, focuses on every aspect of designing and building constructable, efficient, and attractive projects.

## In-House Expertise

One element of Kleinfelder's success derives from its in-house capabilities. "We pride ourselves on being able to provide in-house expertise, especially in areas like geotechnical and construction management," says Jim Frost, Kleinfelder's San Diego, Calif.-based West regional structures manager. "We often are building below-grade structures and have the capabilities to design all types of bridges."

In the bridge world, the greatest challenges may be found below ground, Frost notes, and such challenges can greatly affect the final design and construction of the structure. "The design often is the easy part of the project," he states.

"Our geotechnical services greatly enhance our ability to collaborate easily and create efficient designs," says Robert Torres, a senior program manager who manages the geotechnical department in the San Diego, Calif., office. "We work closely with the designers, especially early in the process. It's not as complicated when you're all under one roof and not emailing and setting up meetings."

The geotechnical department provides earthquake and seismic design, engineering geology, foundation design, geotechnical engineering, and related services. The department "plays an



Kleinfelder conducted an extensive investigation and material evaluation on the 85-year-old North Torrey Pines Road Bridge, in Del Mar, Calif. The result was rehabilitation and a seismic retrofit featuring a new post-tensioned superstructure consisting of 80 custom-built haunched precast, prestressed concrete girders that replicated the existing structure's appearance. All Photos: Kleinfelder.

important role in most of our work, but it often goes unnoticed," Torres says. "We deal with issues from the ground down. People never get to see what we do."

A good example of the work that this department does can be seen in the 85-year-old North Torrey Pines Road Bridge, which underwent rehabilitation and a seismic retrofit in 2015. When the sufficiency rating of the historic 550-ft-long bridge in Del Mar, Calif., had dropped to 19 by 2008, many people thought it should be replaced. However, the community wanted to save the signature bridge. Kleinfelder conducted "an exhaustive investigation and materials evaluation," says Keith Gazaway, principal engineer in the San

Diego, Calif., office. The assessment included delamination surveys, material sampling and testing, and nondestructive and destructive testing. Condition evaluations, seismic retrofit solutions, and replacement options were analyzed and presented in public meetings with detailed visual simulations.

Kleinfelder's efforts resulted in the rehabilitation design of the 15-span, cast-in-place reinforced concrete T-girder bridge with a new post-tensioned superstructure consisting of 80 custom-built haunched precast, prestressed concrete girders that replicated the existing structure's appearance. (For more information about this project, see the Fall 2016 issue of *ASPIRE*®.)

"Torrey Pines was a complex project, with its history, difficulty with constructability in the area, and the number of stakeholders involved," Gazaway says. "It required a complex solution, and that's what we provided."

Another of the firm's signature services is its construction management team, which focuses on a project's constructability in all phases. "We can create a package of review that ensures an efficient, constructable design that goes from examining beneath the ground through construction," says Frost.

In many cases, construction management includes juggling various funding sources, says Gazaway. "There can be complicated decision matrices with various funding sources earmarked for specific purposes," he explains. "Some funding will cover only specific areas, and our clients want us to help their projects qualify for as much funding as possible."

### Bridge Rehabilitation and Replacement Projects

Local officials often want Kleinfelder to evaluate their bridges for both deterioration and functionality. "Many bridges were built in the 1950s and need work," Gazaway says. "At the same time, population growth has boomed, putting more demand on these structures. We evaluate if bridges need to be repaired and also how they could be widened to better handle more traffic."

Usually, the firm develops several alternatives, he adds. "We present the issues [to owners] for all approaches, and let them decide based on their own agenda and needs." In some cases, Kleinfelder's evaluations lead to the rehabilitation of a structure instead of its replacement. A significant portion of the company's work involves either rehabilitating bridges (making minor repairs and upgrades) or retrofitting them (making more substantial improvements). "We do more replacement projects than rehab, but we do a lot of both," Frost says.

Owners today want to spread their funding as widely as possible, leading to more rehabilitation projects, notes Wade Brown, a principal professional in Kleinfelder's Manchester, N.H., office.

"We are performing many more rehabs on the East Coast because of the challenges with the aging infrastructure and the limited funds. The trend is definitely to extend the lives of existing bridges.... [These efforts] range from small-scale projects to major rehabs and partial replacements."

Historic bridges require especially careful evaluations, says Brown. "I don't know if there is a general desire or trend to retain older bridges, but certain bridges have obvious historic value."

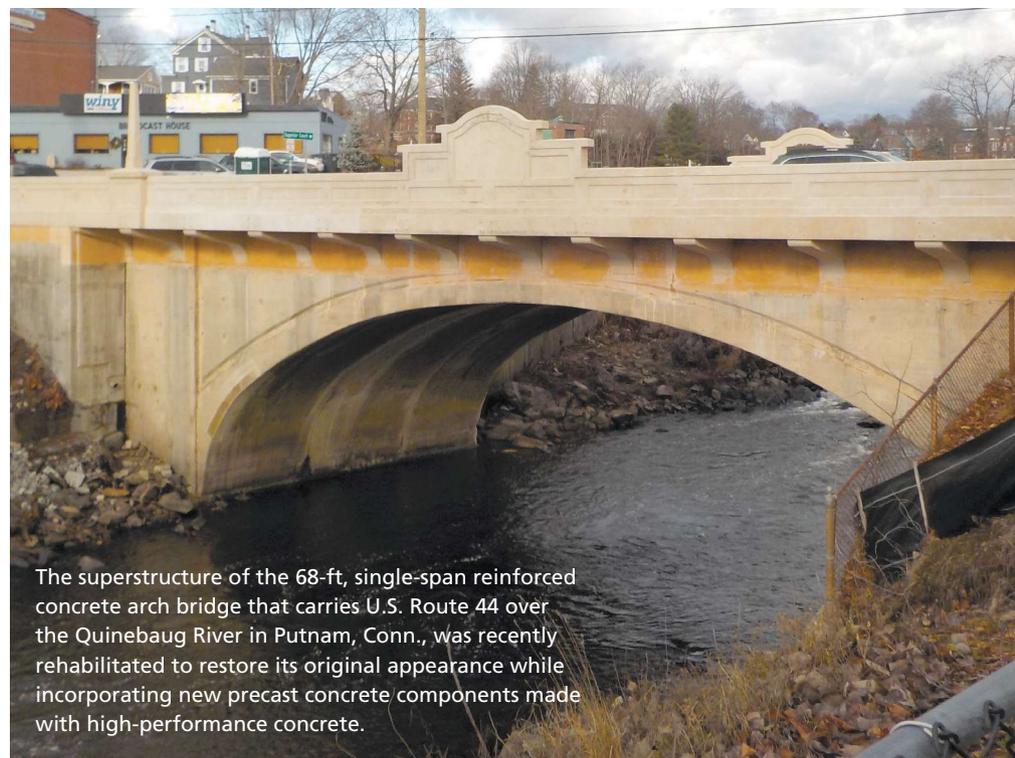
That was the situation with the historic rehabilitation of the U.S. Route 44 Bridge over the Quinebaug River in Putnam, Conn. Kleinfelder was the primary consultant and worked with the in-house bridge and structural-design staff of the Connecticut Department of Transportation. The 68-ft-long, single-span reinforced concrete arch bridge was constructed in 1925 as a World War I memorial. In 2016, its superstructure was rehabilitated to restore its "aesthetic and historic value," says Brown. The project includes precast concrete components with high-performance concrete for sidewalk brackets, ornamental parapets, and light posts to replicate the original appearance.

The bridge's "rehabilitation married new and old, which made it very challenging to design and construct so the new fit perfectly with the old," Brown explains. That was especially the case with the precast concrete parapets, which are highly visible and of architectural importance. "The plans and supplemental specifications included numerous very specific details and instructions to the contractor that were explicit toward establishing an accurate final product."

But Frost warns that repairs are not a panacea. "Rehabs often just push problems down the road by 15 years, which won't solve them," he states. "By that time, costs and traffic loads both will be higher. We need to be doing more life-cycle analyses on all of our infrastructure and make good decisions."

**'Rehabs often just push problems down the road by 15 years, which won't solve them.'**

One recent technological change to Kleinfelder's evaluation process has been the introduction of drones. The firm now has a section that specializes



The superstructure of the 68-ft, single-span reinforced concrete arch bridge that carries U.S. Route 44 over the Quinebaug River in Putnam, Conn., was recently rehabilitated to restore its original appearance while incorporating new precast concrete components made with high-performance concrete.



On the Mid-Coast Light Rail Transit Project in San Diego, Calif., Kleinfelder is providing structural and bridge engineering, geotechnical, environmental, and construction management services. The \$1.7 billion project includes nearly 11 miles of trolley track over multiple bridges and two elevated stations.

in using drones, notes Frost. “They [the drones] help us get a better idea of a bridge’s condition in places we can’t easily inspect,” he says. “They also prove helpful with railroad-track inspections, to ensure the rail is in good shape throughout its length.”

The firm has more it would like to do with drones, he notes. “We’re not completely there yet, but it’s definitely an up-and-coming area, especially for extensive projects. It’s not a mainstream service yet, but it’s coming.”

### Areas of Recent Growth

Through the years, as Kleinfelder’s expertise has grown and expanded, so have the types of projects it undertakes. For example, Kleinfelder has taken on light- and heavy-rail system projects. “We’ve done a lot of transit and heavy-rail projects in recent years, and we expect that will continue due to the market’s direction,” says Frost. “Caltrans [California Department of Transportation] does most of its own design work, but we’ve carved out a niche in city transit work, replacing heavy-rail infrastructure

and larger bridges owned by states and cities but funded in part by FHWA [Federal Highway Administration].”

One such project is the Mid-Coast Light Rail Transit Project in San Diego, Calif., where Kleinfelder is providing structural and bridge engineering, geotechnical, environmental, and construction management services. The \$1.7 billion project includes nearly 11 miles of trolley track over multiple bridges and two elevated stations. “We’re mainly using cast-in-place concrete box-girder bridges, but there are a few precast concrete girder bridges and concrete slabs,” says Gazaway.

The geotechnical office has also been involved in this project, doing 385 exploratory borings over the 11-mile length and providing seismic analysis for design criteria on earthquake loads, site accelerations, fault studies, and other needs. “We worked closely with the structures team to determine how the design could tolerate movements,” says Torres. Ultimately, 10-ft-diameter concrete piles (drilled shafts) were installed

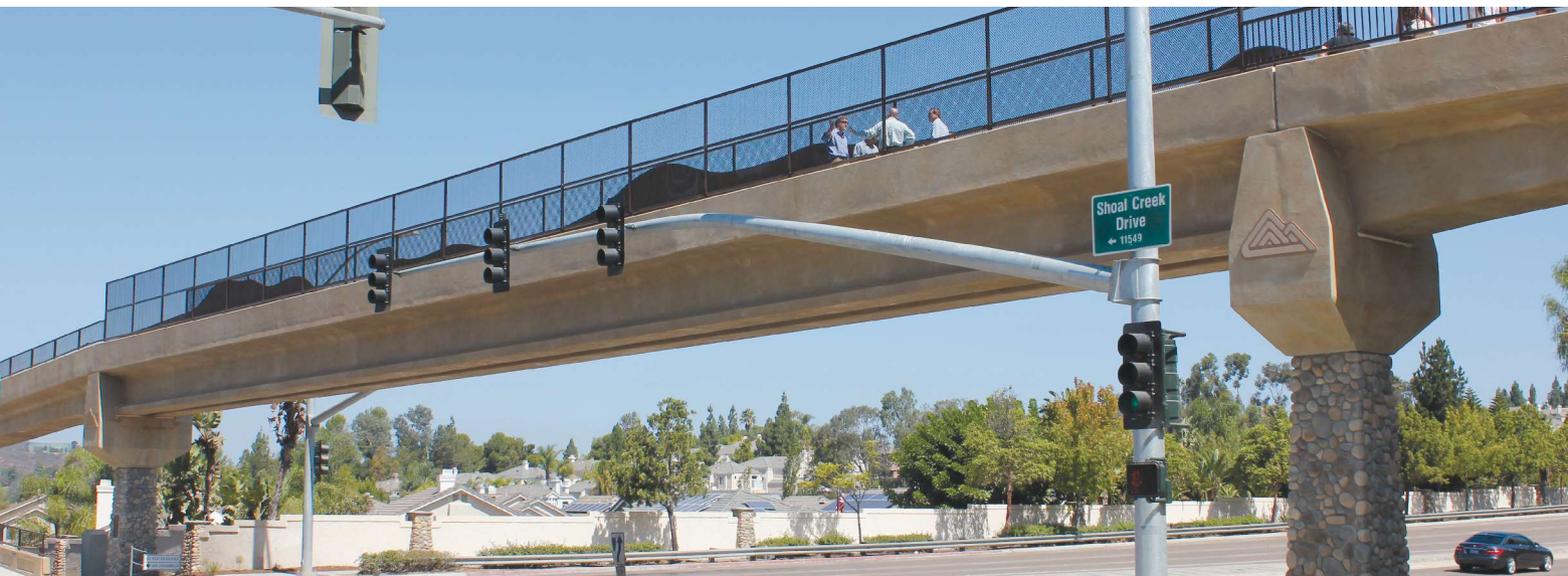
to a depth of 150 ft. “These were large foundations for a river crossing.”

Another area of growth has been pedestrian bridges, which often require more aesthetic attention and community involvement. An example is the Ted Williams Parkway Pedestrian Overcrossing in San Diego, Calif., for which Kleinfelder provided environmental planning and design services. The bridge provides a direct connection over a busy intersection for children attending an elementary school.

“The project had a lot of community involvement,” Gazaway explains. “Safety was at the forefront, and the community was particularly sensitive to its construction.” The design features 140-ft-long precast concrete bulb-tee girders, which had not previously been used in southern California. Kleinfelder worked closely with the precaster to ensure that the 67-ton girders could be fabricated and transported safely to the site.

Aesthetics also were a key concern for

The Ted Williams Parkway Pedestrian Overcrossing in San Diego, Calif., allows schoolchildren to safely cross a busy highway. The bridge features 140-ft-long precast concrete bulb-tee girders and unique columns that match the wall structures in the neighborhood.





The Mid-Coast Light Rail Transit Project primarily features cast-in-place concrete box-girder bridges with a few precast concrete girder bridges and concrete slabs. The bridges range in length from 73 to 4600 ft.

the community, he notes. Kleinfelder coordinated the bridge's architectural treatment with the City of San Diego and the Carmel Mountain Ranch Community, leading a series of meetings and field trips with the neighborhood's architectural committee to discuss visual options and local interests. With residents' input, Kleinfelder designed the bridge aesthetics and landscaping to complement the theme of the surrounding neighborhood. This work included concrete stain, stone cladding, community icons, and decorative railings portraying familiar mountain scenes.

### Looking to the Future

Projects are often being completed faster, thanks to the use of accelerated bridge construction (ABC) techniques. "Owners are more open to ABC thanks to FHWA's encouragement," Frost says. As part of that, he'd like to see more attention and encouragement put into the up-front elements of ABC, especially streamlining and accelerating the permit process.

"We need to work harder from inception to when construction begins," Frost states. "We talk about ways to build faster, but we need to talk about the five to ten years it takes to get the plans to construction. We need to get everyone focused on moving faster, including resource agencies, coastal commissions, and historical groups..."

**'We need to get everyone focused on moving faster, including resource agencies, coastal commissions, and historical groups...'**

That's not to say they should take shortcuts, he stresses. "A lot of people need to weigh in, but many bridges we build aren't that controversial and should be able to get going quicker. We spend a lot of time studying issues to prove that point."

Frost also worries about the supply of skilled labor and materials to build infrastructure projects once they are funded. "Sooner or later, the infrastructure will have to be addressed," he says. "I'm concerned especially about having qualified engineers available to do design work as well as contractors and access to materials. There could be shortages all around."

As civil engineers retire, they will need to be replaced. "We will lose a lot of senior leadership and not have college graduates to fill in," Frost warns. "We need to convince more students to go into engineering today."

Kleinfelder wants to help resolve that issue by going into the community to promote engineering and the challenges and rewards of civil engineering careers. Staff from the San Diego, Calif., office recently took part in a high school program, in which they talked to students about seismic conditions. Their presentation included a shake table to show how earthquakes affect structures.

Like his colleagues, Torres has become involved in educational outreach. He serves on the board of the engineering curriculum at a local high school; visits classes at the elementary, high school, and university levels; and hosts student visits to his office lab.

### Kleinfelder's History

In 1961, Jim Kleinfelder established Stockton Testing and Controls in Stockton, Calif., to test construction materials. In 1963, he bought out his original partners and expanded to Merced, Calif., beginning a series of expansions and mergers.

Kleinfelder is a privately held firm. It grew from 30 employees and approximately \$300,000 in annual revenue by the end of the 1960s to more than 1950 employees with more than \$325 million in revenues by 2010.

In 2016, George J. Pierson, formerly president and chief executive officer of Parsons Brinckerhoff, became the firm's fifth CEO. The company was listed as the 55th top design firm in *Engineering News-Record's* 2017 rankings.

"Students at all levels get very excited when we show them what we do," he says. One recent high school class saw the team test concrete cylinders to failure and examined soil core samples with various strata. "They were amazed, because they didn't know jobs like this existed."

**'Students at all levels get very excited when we show them what we do.'**

Torres saw how these outreach efforts can succeed when he recently received an email from a student who now attends California Polytechnical Institute at San Luis Obispo. "He thanked me for letting him visit and said it made him want to work in the field," Torres says. "He's now studying civil engineering at the university."

Kleinfelder's team will continue to balance various design needs, stakeholder concerns, constructability issues, and every element of the project from beneath the ground up. As it does, the company is also keeping an eye on the future and helping to prepare future generations for what no doubt will be even more challenging projects. **A**

# Benefits of the FHWA-NHI Strut-and-Tie Modeling Workshop

## An Attendee's Perspective

by Dr. Tess Ahlborn, Michigan Technological University

To meet the current and future needs of our ever-changing society, engineers must keep their skills and knowledge up to date. Such discipline is required of new graduates and more-experienced engineers alike. Even if you are fully qualified, it is essential that you keep abreast of changes in the engineering profession. Continuing education courses can strengthen and broaden your knowledge base, and they will help you master needed skills at any stage of your career. Continuing education is also a requirement of licensure in most states.

We can, of course, take webinars and online courses to learn about new bridge construction practices and improve our bridge design skills. However, when I participated in the “FHWA-NHI Strut-and-Tie Modeling (STM) Workshop” at the 2018 PCI Convention and National Bridge Conference in Denver, Colo., I was reminded of the unique value of collaborative and interactive education—there is nothing quite like being in the room with industry authorities and informed colleagues.

STM has long been established as the preferred analysis method for deep beams and disturbed regions in concrete structures. STM is appropriate for analysis and design of bridge elements such as beam ends, diaphragms, corbels, beam ledges, deep beams, and pile caps.

Despite the importance of STM, introductory concrete design courses typically do not cover the topic, and many design engineers do not feel confident about their understanding and use of the method, especially if they

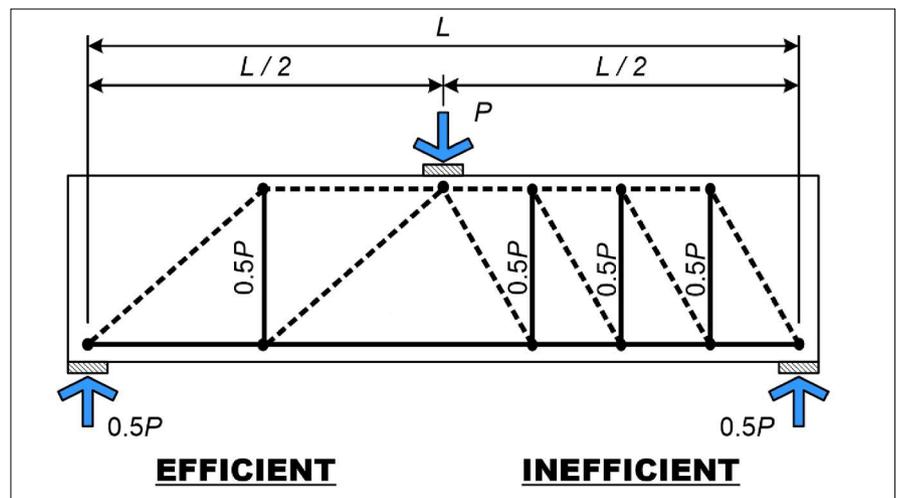
have been using a traditional sectional analysis requiring a two-step design process—one for flexure and one for shear. With the American Association of State Highway and Transportation Officials’ (AASHTO’s) recent adoption of new STM provisions in Section 5 of the *AASHTO LRFD Bridge Design Specifications*,<sup>1</sup> engineers must clearly understand and be able to apply the concepts and details of STM.

The STM workshop I attended was run by the Federal Highway Administration (FHWA) and National Highway Institute (NHI) and geared toward bridge engineers at all levels of STM experience, from beginner to advanced. When I attended it, I was not a novice in STM. I was first introduced to the method as a PhD student at the University of Minnesota nearly 30 years ago, thanks to Professor Cathy French and her progressive technical course content, and I have since

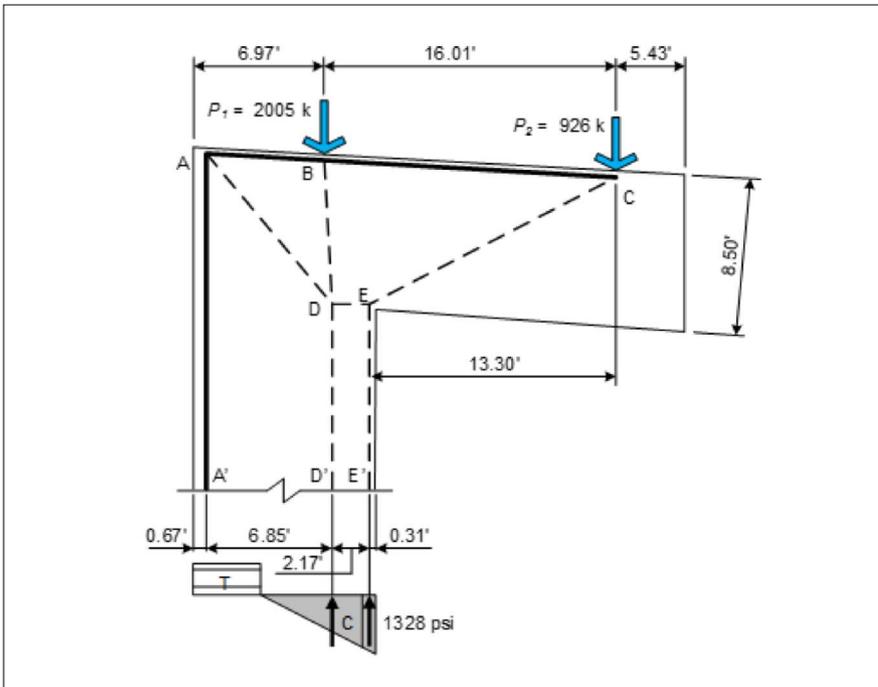
included a few lectures and homework to introduce STM to my own students in a graduate-level bridge design course. Therefore, for me, the workshop offered an excellent opportunity to sharpen my STM skills and gain some practical experience. The workshop was also well suited for introducing students to STM, especially when curriculum requirements and other course content limit the classroom time available for some technical topics.

In the workshop, industry experts presented an in-depth introduction to STM fundamentals and then guided attendees through simple to advanced STM scenarios commonly seen in bridge engineering. Attendees actively participated, defining truss systems and evaluating designs.

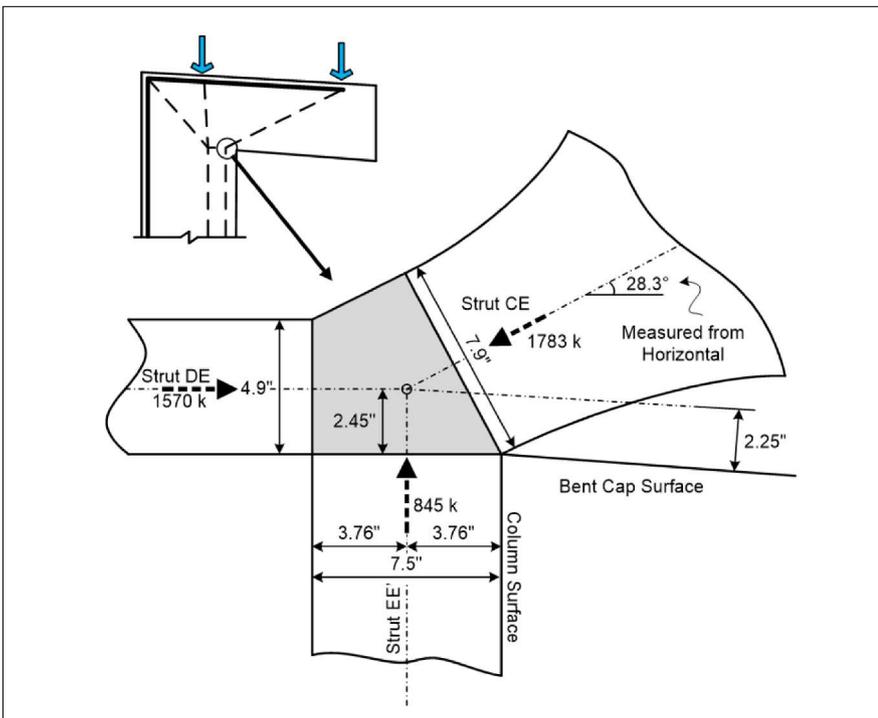
The following are critical points from the workshop to keep in mind when working with STM:



An example of efficient and inefficient strut-and-tie models. All Figures: Federal Highway Administration.



Strut-and-tie model of a cantilever bent cap.



Example of geometry and forces at a node.

- STM uses an engineering art approach, where stress flows are visualized into trusses, resulting in many possible solutions. Preparing the STM model includes defining B- and D-regions, proportioning concrete compression struts and reinforcement tensile ties, and identifying nodes where struts and

ties intersect. Proper implementation and analysis will result in an efficient concrete member design, with quantities and layout for reinforcement and bearing areas, and consideration for serviceability requirements.

- Understanding of fundamental concepts is necessary to accurately

implement STM. For example, the efficiency of a strut-and-tie model depends on load path; therefore, the most efficient model is a truss representing a direct load path. An efficient model, as shown on the previous page, will optimize the shear reinforcement. Boundary conditions are also critical in STM applications.

The workshop I attended engaged participants through a variety of STM example problems. The cantilever bent cap example was especially interesting to me. Maintaining equilibrium in the truss is particularly important with the unbalanced loading of the cantilever. Strength checks, which are necessary for the struts, ties, and nodes, included an enjoyable level of geometry for defining nodal dimensions. Crack-control reinforcement and anchorage requirements for ties were also addressed.

The workshop unquestionably exceeded my expectations. It helped me hone my STM skills and acquire practical experience through engaging discussions with a diverse cadre of bridge engineers. The workshop was extremely informative and well organized, and it challenged participants to blend their creative and critical thinking skills as they came to understand the proper use of STM. Based on the in-depth discussions facilitated by the expert instructors, I can assure you that there is undoubtedly a need for this training at all levels of the profession.

## Reference

1. American Association of State Highway and Transportation Officials (AASHTO). 2017. *AASHTO LRFD Bridge Design Specifications*. 8th ed. Washington, DC: AASHTO.

## EDITOR'S NOTE

*All figures provided by FHWA for this article were developed for the NHI Course No. 130126, Strut-and-Tie Modeling (STM) for Concrete Structures, Publication No. FHWA-NHI-17-071. This course was the topic of an article in the Winter 2018 issue of ASPIRE®. Additional discussion of this course is planned for future issues.*

PROJECT

# 35TH STREET PEDESTRIAN BRIDGE

by John Hillman, Parsons Construction Group, and Brian Umbright, EXP

Overview of the completed bridge looking north. All Photos: Dave Burk Photography.

Architecturally, Chicago is considered one of the world's greatest cities. This recognition is due in no small part to the *Plan of Chicago*<sup>1</sup> or the "Burnham Plan," the early-20th-century vision of architects and urban planners Daniel Burnham and Edward H. Bennett. In particular, Burnham and Bennett advocated for protection of the Chicago lakefront with an extensive network of parks bordering Lake Michigan that could never be commercialized. In 1973, the Lake Michigan and Chicago Lakefront Protection Ordinance further solidified this commitment to a public lakefront and included requirements to provide universal access to the lakefront for all of Chicago's neighborhoods.

Over the years, the urban plan led to the construction of numerous bridges and underpasses to allow pedestrians to safely cross Lake Shore Drive and access the lakefront. The original 35th Street Pedestrian Bridge built in the 1930s was one such access point. However, by the early 21st century, the bridge no longer served its purpose. It was classified as structurally deficient and did not meet the requirements of the Americans with Disabilities Act.

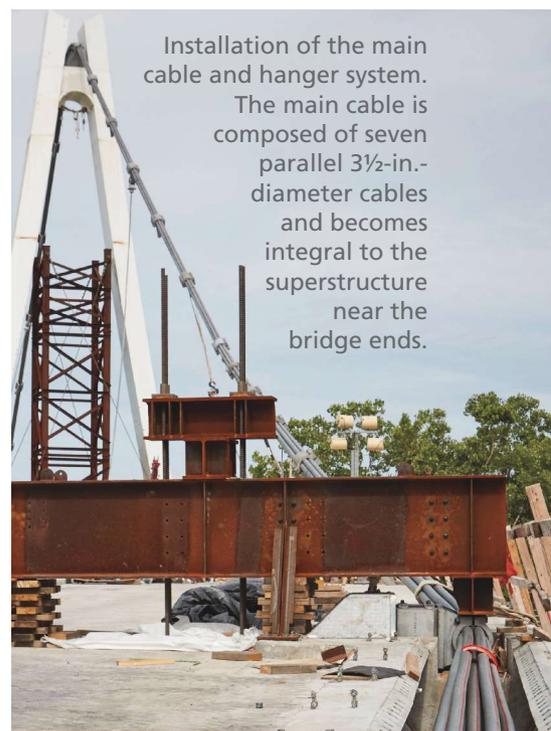
## Call for Proposals

In 2003, the Chicago Department of Transportation (CDOT)—in conjunction with the Chicago Architecture Foundation—initiated the "Bridging the Drive Competition" to solicit concepts for replacement structures for four pedestrian crossings of Lake Shore Drive, including the 35th Street Bridge. The City intended to create iconic bridges at each of these locations. The international competition garnered 67 proposals from 23 firms. The concept submitted by EXP was selected as the winning entry for the 35th Street location.

## Project Challenges and Design Specifications

The 35th Street Pedestrian Bridge invokes the classic principles of a self-anchored suspension bridge, but with a twist. It crosses over Lake Shore Drive on a horizontally reverse-curved alignment, which provides for panoramic views of Lake Michigan and the Chicago skyline. The S-shaped curvilinear alignment became a necessity due to the unique site constraints—the western approach is between two historical landmarks, the Stephen A. Douglas Memorial and a

former Civil War hospital. The alignment also minimizes the distance of the Lake Shore Drive crossing, limits the required approach grades, preserves a grouping of mature trees in Burnham Park, and achieves the required vertical clearances over Lake Shore Drive and the railroad.



Installation of the main cable and hanger system. The main cable is composed of seven parallel 3½-in.-diameter cables and becomes integral to the superstructure near the bridge ends.

## profile

### 35TH STREET PEDESTRIAN BRIDGE / CHICAGO, ILLINOIS

**BRIDGE DESIGN ENGINEER:** EXP, Chicago, Ill.

**CONSTRUCTION MANAGER:** CH2M, Chicago, Ill.

**PRIME CONTRACTOR:** McHugh/Araiza Joint Venture, Chicago, Ill.

**POST-TENSIONING CONTRACTOR:** James McHugh Construction Co., Chicago, Ill.

**OTHER MATERIAL SUPPLIERS:** Post-tensioning strand and hardware: DYWIDAG-Systems International USA, Bolingbrook, Ill.; Suspension cable: WireCo WorldGroup, Kansas City, Mo.



Aerial view during installation of the main cable. The suspension cable supports the outside of the horizontal reverse-curvature bridge.

The bridge's single suspension cable is aligned to support the outside of the curves on the respective spans. The result offsets the inherent torsional tendencies of curved beams. Simultaneously, the horizontal component of force in the skewed hangers and the forces induced in the ends of the deck from the anchorages of the suspension cable create a self-equilibrating suspension structure.

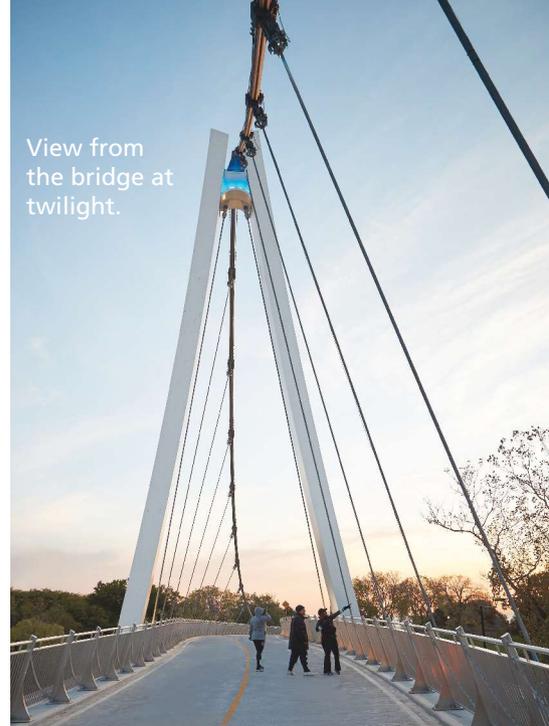
The bridge comprises two 250-ft-long main spans and two 60-ft-long approach spans, for a total length of 620 ft. The superstructure's cross section is composed of a triangular high-performance concrete (HPC) box girder, which is 32 ft 6 in. wide and accommodates a 20-ft-wide pathway. The position of the apex of the triangular section varies along the length of the bridge. This variation not only reflects the asymmetrical configuration of the suspension cable but also results in an efficient cross section. The section along the free edge at the inside of the superstructure curvature is deeper and stiffer than the section along the outside, which is supported by the cable hangers.

The rigidity of the closed cross section helps control torsional rotations resulting from the eccentricities of the center-of-mass and hangers. Additional compensation for the torsional moments is provided by longitudinal post-tensioning (PT) tendons placed along the bottom slab at the inside of the curves. The tangential component of force of these tendons applies a counter-clockwise rotation that offsets a portion of the dead load torsional moment in the section. The nearly 6000 kip anchorage force from the longitudinal PT also balances the enormous anchorage forces from the main suspension cable. To help with internal stability of the box section, the superstructure also contains transverse PT tendons spaced roughly 5 ft apart along the entire length of the bridge.

The aerodynamic cross section combined with the concrete mass serves to minimize pedestrian- and wind-induced accelerations. This desired dynamic behavior and the reduced maintenance costs were two of the major reasons why concrete was selected instead of steel for the superstructure. During the design phase, the behavior of the structure was validated through wind and vibration analyses.

For the superstructure and substructure components, specifications dictated the use of HPC with minimum compressive strengths of 6000 and 4000 psi, respectively. CDOT, which has long been a proponent of HPC, developed a thorough performance specification that required targeted proportions but gave the contractor ultimate flexibility and responsibility for meeting strength and performance parameters.

The contractor was also given broad latitude to use air-entraining admixtures and high-range water-reducing



View from the bridge at twilight.

admixtures to meet the physical-property parameters. To increase durability, chloride permeability resistance was specified to be less than 2000 coulombs at 28 days. To further enhance durability and improve final pathway smoothness, a 2-in.-thick latex-modified concrete overlay was placed on the box girder.

Extra care and attention were taken to design bridge details that would enhance the unique structural form of the bridge. The 117-ft 9-in.-tall central pylon uses an A-shape to resist all lateral-force components. The two steel trapezoidal-box legs of the pylon have slow, graceful curves that complement the natural curvature of the suspension cable. To simplify constructability and control long-term creep deflections in the superstructure, the pylon foundation pedestals are made of reinforced concrete supported on micropiles.

The piers efficiently transmit the torsional forces out of the superstructure into the foundations and have the same lines as the pylon, while upholding the asymmetrical character

## CHICAGO DEPARTMENT OF TRANSPORTATION, OWNER

**BRIDGE DESCRIPTION:** Self-anchored, mono-cable suspension bridge on a reverse circular curve with a triangular-shaped post-tensioned concrete box-girder superstructure

**STRUCTURAL COMPONENTS:** 620-ft-long cast-in-place, post-tensioned concrete box girder comprising two 250-ft-long main spans and two 60-ft-long approach spans; cast-in-place concrete piers, pylon footings, and abutments; and micro-pile foundations

**BRIDGE CONSTRUCTION COST:** \$26 million

**AWARDS:** Grand Award, American Council of Engineering Companies (ACEC), 2018; Honor Award and Best in Category – Structural Systems, ACEC of Illinois, 2018.



Elevation view from northbound Lake Shore Drive during construction. The contractor chose to construct a temporary bridge to build the bridge.

of the overall design. Longitudinally, the piers are thin walls with no bearings provided at these supports. Instead, the superstructure was connected to the piers using PT bars after all hangers and girder PT were completed, allowing for reduced moments in the piers from long-term creep of the superstructure.

There are closed abutments at each end of the structure, with retaining walls that continue the line of the sloped edge of the superstructure. The overall slender appearance of the structure was maintained by avoiding earth anchorage at the abutments and using the self-anchoring design. The superstructure is supported on disc bearings at the abutments, resulting in only four bearings in the entire structure. To accommodate pedestrian clearances at the hangers, the out-to-out width of the superstructure follows a slightly different alignment than the centerline of the

Customized triangular box-girder superstructure formwork in progress.

traveled way, and they only coincide at the pylon. Thus, the abutments are narrower than the superstructure cross section, and the setback provides an ideal location to leave the ends of the main suspension cables exposed.

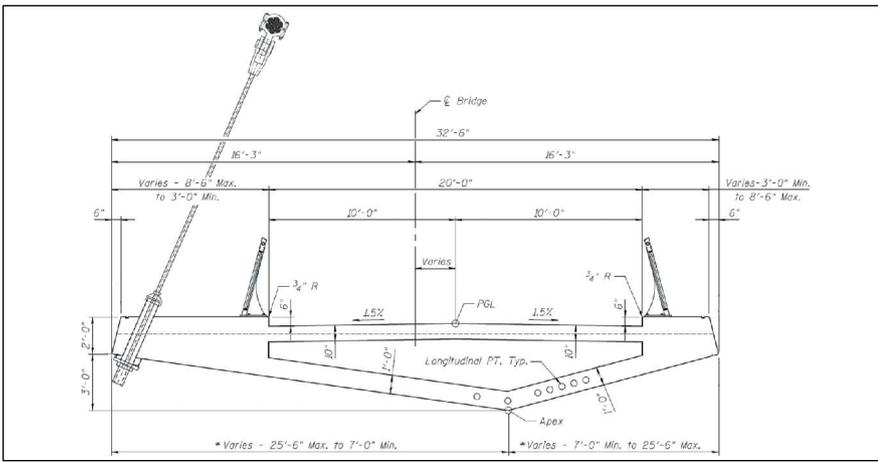
The scale of the bridge posed some interesting challenges regarding the design of the main suspension cable, which was too short for conventional spinning but too long for an off-the-shelf structural single-strand system. A compromise was reached by developing a cable system comprising a cable assembled out of seven 3½-in.-diameter conventional structural strand cables bundled together. Each cable was placed individually over a saddle at the pylon and anchored at the end of the bridge with its own spanner nut to accommodate force adjustments. Once the main cables were in place, they were banded together with clamps that comprised the clevis connection for the hanger cables. All the suspension cables and 2¾-in.-diameter hangers—

ASTM A586 Grade 2 strand (minimum tensile strength of 220 ksi) with Class A weight galvanized coating—have been left exposed and visible.

To transfer the anchor force of the main cable all the way to the end of the superstructure, the cables deviate both vertically and horizontally at the pier locations and become internal to the superstructure cross section. The vertical deviation is an outcome of the catenary drape and grade, and the horizontal deviation is aided by a custom horizontal rocker bearing at the deck level. Subsequently, the only deviation at this point is horizontal, and the seven cables are splayed to provide adequate spacing at the hexagonal anchorage at the end of the bridge.

The bridge has custom-designed stainless steel railings that mimic the shapes of other elements. Throughout the bridge, decorative LED lighting is hidden within the railing and suspension system to be highly functional but not





Typical cross section of the cast-in-place concrete box girder showing the triangular void. All Figures: EXP.

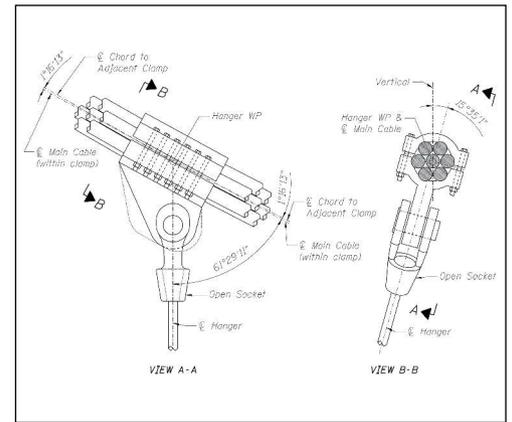
detract from the simplicity of the bridge form. To enhance the design's simplicity, the bridge has been left in its natural concrete state and only the steel pylon elements are painted.

The original design provided for a cast-in-place segmental scheme using form travelers for the superstructure to limit formwork requirements. However, the contractor chose to use a more conventional cast-in-place method—essentially building a bridge to build the bridge. An elaborate steel beam and tower falsework system was erected with a plywood deck to create a level working platform from which the contractor built the elaborate customized formwork system to place concrete for the superstructure. The concrete-placing sequence was broken down into five longitudinal castings with the bottom and top slabs of the cross section placed separately each time. To avoid erecting

and pulling formwork in the triangular void, the contractor used lightweight foam blocks that could stay in place as formwork for the top slab. The formwork and falsework were not removed until the main cable and hangers were installed and the bridge was self-supporting, and only then did the beauty and elegance of the final form become evident to the public.

### Conclusion

The 35th Street Pedestrian Bridge opened in November 2016 after more than two years of construction. This project was funded by a partnership of the City of Chicago, the State of Illinois, and the Federal Highway Administration. By its very nature, the project was more expensive than a traditional crossing, but the costs are justified by the bridge's unique design, architectural significance, and positive impact on the surrounding



Main cable-clamp detail at a hanger. All cables are ASTM A586 Grade 2 strand with Class A weight galvanized coating.

community. Because the bridge design pulls the pathway away from the roadway and railway, the crossing is relatively tranquil. Also, the curvilinear alignment provides ever-changing vistas for pedestrians to enjoy. Finally, the residents of Chicago's Bronzeville neighborhood have gained an essential link to the lakefront and a beacon for their community.

*John Hillman, previously with EXP, is now technical director with Parsons Construction Group in Westminster, Colo., and Brian Umbright, is vice president, Transportation, with EXP in Chicago, Ill.*

### Reference

1. Burnham, D.H., and E.H. Bennett. 1909. *The Chicago Plan*. Chicago, Ill.: The Commercial Club. <https://archive.org/stream/planofchicago00burnuoft>.



## AESTHETICS COMMENTARY

by Frederick Gottemoeller

An underappreciated characteristic of a structure's alignment is how it aims the users' view toward a particular feature. The extreme case is a straight railroad track. When you look along such a track, you can hardly take your eyes off the distant point where the rails seem to come together. Straight bridges direct your eye toward whatever lies ahead along their tangent. In contrast, curved bridges sweep your eye over the landscape, so you must focus in turn on all of the features of the visual field. In the case of the 35th Street Bridge, that visual field is the expansive shore of Lake

Michigan or, going the other way, the architecture of the Chicago skyline.

The hanger arrangement, which supports the deck first on one side of the bridge and then the other, further directs your point of focus. When the hangers are seen together as you look along the bridge, they form a curved plane along the outsides of the curves, which encourages you to concentrate on whatever you can see from the inside of the curve. Thus, the hanger system subtly switches your focus from one side of the bridge to the other.

The sloped soffits of the triangular cross section make it impossible to judge the depth of the cross section at the section's apex. Travelers along Lake Shore see only the depth of the much thinner aerodynamic edge. To them, the bridge seems far thinner, and thus lighter, than it really is.

Finally, this bridge asserts a sense of unity. The angles of the tower legs, the hangers, the aerodynamic edges, the angles of the piers and the abutment walls, and even the stanchions of the railings are all sloped in the same direction and at similar angles. The curves of the tower legs emulate the curves of the suspension cables. Each part seems perfect for this bridge and would look out of place on another. This bridge is a masterpiece. The designers and the City of Chicago can be proud of having brought it into existence.

## PROJECT

# ST. CROIX RIVER CROSSING

by Craig Lenning, HDR, and Don Bergman, COWI North America Ltd.

A view of the St. Croix River Crossing looking toward the Wisconsin shore. The unique shapes of the rounded, “reed-like” split piers and the cantilevered pedestrian overlook are visible at the pier in the foreground. Photo: HDR.

The 6670-ft-long replacement bridge crossing the St. Croix River between Minnesota and Wisconsin includes a seven-span, 3365-ft-long extradosed main unit over the river and a dual seven-span, 1715-ft-long approach bridge with a 960-ft-long off-ramp and a 630-ft-long on-ramp. These structures were constructed with a combination of precast and cast-in-place concrete construction.

The extradosed bridge, which is a hybrid between a concrete segmental box-girder and a cable-stayed bridge, has four 600-ft main spans and a total length of 3365 ft between expansion joints. The out-to-out dimension of the bridge deck is 98 ft 6 in. The approach

bridge is located on a 3-degree horizontal curve (1910 ft radius) with a 6% superelevation and includes a 1000-ft vertical curve before the alignment transitions to a tangent 1.74% upward grade from Minnesota to Wisconsin. The distance between the bridge deck and the water line varies from approximately 100 to 150 ft.

The bridge was opened to traffic in 2017, although construction continues. When completed, the St. Croix Crossing will be the second extradosed bridge built in the United States and the longest in North America.

### Project Approval Process

The St. Croix Crossing project has

a long history. Talk of a new bridge began in 1951, with advocates for new construction arguing that the existing Stillwater Lift Bridge was hindering economic growth and causing traffic delays. However, the St. Croix River is protected by its designation as a National Wild and Scenic River, and, for decades, conservationists and some local community members opposed the construction of a new bridge because of its potential environmental impact and fiscal costs. To address these concerns and comply with federal environmental regulations, a new bridge project would need to include mitigation strategies to protect all of the following:

- Historic properties
- Threatened and endangered species

## profile

### ST. CROIX RIVER CROSSING / OAK PARK HEIGHTS, MINNESOTA, AND ST. JOSEPH, WISCONSIN

**BRIDGE DESIGN ENGINEER:** HDR, Minneapolis, Minn., and COWI North America Ltd., North Vancouver, BC

**PRIME CONTRACTOR:** Lunda Ames Joint Venture (Lunda Construction Company, Black River Falls, Wisc., and Ames Construction Company, Burnsville, Minn.)

**OTHER CONSULTANTS:** Bridgescape, LLC, Columbia, Md.; Illumination Arts, Bloomfield, N.J.; M-P Consultants, St. Louis Park, Minn.; Prime Engineering, Baltimore, Md.; Rani Engineering, Minneapolis, Minn.; RWDI, Guelph, ON; Weidinger Associates, New York, N.Y.

- Wooded wetlands on the Minnesota bank
- Highly erodible soils on the Wisconsin bluff
- Water quality in the watershed

The project would also need to relieve traffic congestion, provide safe passage for vehicles and pedestrians, and offer an aesthetically appropriate design for the site.

In 1996, a new design was proposed, and, in the early 2000s, a stakeholder committee was formed while an environmental impact statement (EIS) was prepared to address the many issues that were preventing the bridge project from moving forward. In 2006, the St. Croix River Crossing Supplemental Final EIS (SFEIS)<sup>1</sup> documented the important social, economic, and environmental impacts associated with the crossing and concluded that the preferred alternative structure would be an extradosed bridge. The SFEIS identified the following key attributes of the proposed extradosed form:

- “Minimizes impacts on the Wisconsin and Minnesota bluffs by locating [the structure] in an existing bluff cut in Minnesota and an existing bluff ravine in Wisconsin;
- “Reduces the number of piers and apparent mass of the structural components, decreasing adverse visual impacts on the St. Croix River; and
- “Provides a signature bridge design.”<sup>1</sup>

The SFEIS further noted that “The Preferred Alternative extradosed bridge introduces a visually unique bridge type to the river corridor, a type that does not correspond to the nearby Lift

Bridge or to other bridge types found along the St. Croix River and presents a visually dramatic form and structural appearance to viewers and users both off and on the bridge.”<sup>1</sup>

Also in 2006, the Federal Highway Administration (FHWA) issued a record of decision to allow the project to proceed. However, the project also required approval of the National Park Service (NPS), the federal agency responsible for administering the Wild and Scenic Rivers Act. In 2010, NPS determined that it did not have the legal authority to permit any new construction in the riverway unless federal legislation provided a project-specific exemption.

After more than half a century of legal and political battles, Congress passed and President Barack Obama signed legislation in 2012 that authorized exemptions for the project. Bridge design began in 2012 with an early foundation construction package let in the spring of 2013 and a final construction package let in November 2013. Construction started in the spring of 2014.

### Refining the Extradosed Bridge Design

After FHWA issued its 2006 record of decision, MnDOT completed the joint visual quality manual (VQM) in 2007 to define the aesthetic aspects of the proposed extradosed structure.

The 2007 VQM proposed a baseline extradosed structure with maximum 480-ft-long main spans and six piers in the river. The main extradosed bridge would have a total length of 3460 ft.

To align with the visual theme identified in the VQM, the proposed structure

would use twin concrete box girders, 19 ft 8 in. in depth, with rounded girder webs and soffit. The 98-ft 6-in.-wide deck carried two lanes of traffic in each direction with shying strips (also known as a shy distance) at the median and wide outside shoulders. The overall width included a 12-ft-wide lane for pedestrians and bikes cantilevered from one side of the deck as well as cantilevered pedestrian outlooks at the main piers. The extradosed cable stays would be anchored to the outside of the twin box girders, and the box girders were connected transversely by solid diaphragms.

The proposed piers were rounded and “reed-like” in form, with three legs to carry the superstructure loads down to the drilled-shaft foundations in the river bed. To achieve continuity of the extradosed superstructure without deck joints or sliding bearings at pier locations, flexible twin legs were used beneath the crossbeam to allow longitudinal thermal and time-dependent length effects. This permitted the ends of the twin box girders to frame into the piers, thereby minimizing the visual impact of the pier crossbeams, which were kept largely within the depth of the deck section. The pile caps were located at the mudline to ensure that the piers rising out of the river were as visually clean as possible.

In 2010, an addendum to the VQM was issued to further refine the visual aspects of the structure. Most importantly, this addendum, which is quoted in the following bullets, described how the revised structure fit the “organic” theme for the structure:

- “The parts of the bridge look as if they were found in nature, or shaped by natural forces.
- The vertical pier forms are reed-like;

## MINNESOTA DEPARTMENT OF TRANSPORTATION AND WISCONSIN DEPARTMENT OF TRANSPORTATION, OWNERS

**BRIDGE DESCRIPTION:** A 3365-ft-long, post-tensioned, precast concrete segmental box-girder extradosed bridge spanning the St. Croix River with 1715-ft-long approaches, a 960-ft-long off-ramp, and a 630-ft-long on-ramp for a total length of 6670 ft

**STRUCTURAL COMPONENTS:** Cast-in-place and precast concrete segmental box-girders, cast-in-place concrete cross-beam and towers, drilled shafts (river foundations), and pile footings (approach foundations)

**BRIDGE CONSTRUCTION COST:** \$341,600,000 + \$40,000,000 early foundation contract = \$381,600,000 total

**AWARDS:** Finance & Commerce: Top Projects of 2017; American Council of Engineering Companies (ACEC) Minnesota Engineering Excellence Awards: Grand Award, Grand Conceptor Award, and People’s Choice Award; ACEC National Engineering Excellence Honor Award; American Public Works Association Public Works Project of the Year—Transportation Category, More than \$75 Million; Slag Cement Association Project of the Year—Innovative Applications Category

the girders are rounded and tapered like bones or tree branches; and walls, barriers and railings are curved and blended into the larger forms.

- Transitions are gradual and smooth; edges are soft and curved; and colors are unified and natural expressions of their materials.”<sup>2</sup>

By using a slightly deeper crossbeam at the piers, the middle leg of the three-legged piers could be removed, providing a lighter, cleaner, and more aesthetically pleasing pier arrangement with a smaller footprint in the environmentally sensitive river.

In the 2010 design concept, the lane for pedestrians and bikes was moved to the inside of the extradosed stay cables, eliminating the cantilevered sidewalk. The change provides visually consistent leading edges on both sides of the deck, ensuring that the curved “organic” nature of the girder webs would be clearly exposed from both viewing directions.

The cantilevered pedestrian outlooks at the main piers remained in the 2010 update, but they were given a rounded soffit to further enhance the visual theme for the structure. The cable anchorages, which were exposed on the outer edge of the deck in the 2007 arrangement, were now covered by a continuous shroud to give the deck edge a cleaner continuous line.

The 2010 design reduced the depth of the deck section from 19 ft 8 in. to 18 ft. Both single and twin box-girder

sections were assessed for the deck section, and both were considered to be structurally viable. It was noted that both deck sections could be constructed by cast-in-place methods, but the twin box-girder arrangement would be better suited to precast concrete segmental-type construction. Strutted diaphragms between the twin box girders replaced the solid diaphragms in the 2007 arrangement, giving the 2010 design a more interesting and lighter appearance from the underside, which would be visible from the nearby Stillwater, Minn., community. Internal ribs were used to adequately transfer the vertical cable forces across the wide deck section.

### Final Design of the Extradosed Bridge

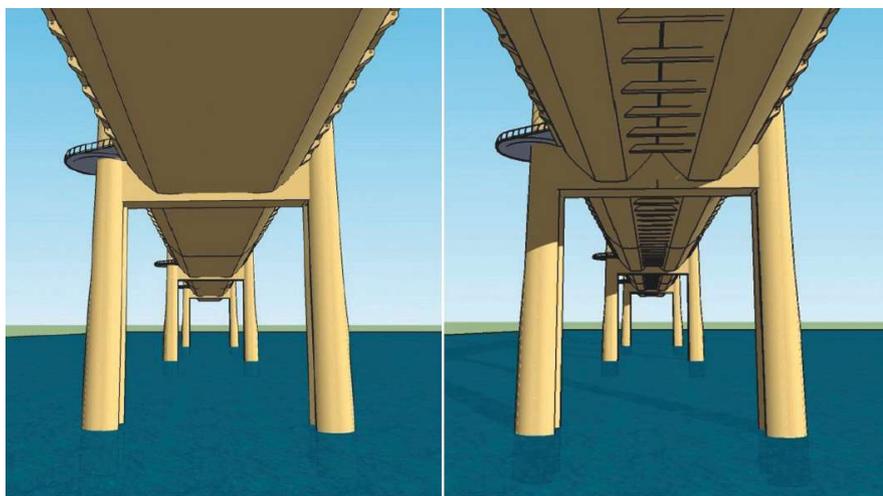
Once the exemption from the Wild and Scenic Rivers Act became law, work on the final detailed design of the structure started in late 2012. Further assessment of the span lengths resulted in the decision to lengthen the main spans to 600 ft, for a 3365-ft-long extradosed structure. The final structure has five piers in the river (one less than the 2010 arrangement), which further reduces the bridge’s footprint in the river. The final arrangement also eliminates the earlier proposed extradosed pier on the sensitive Wisconsin bluff slope, and the extradosed piers now are clearly visually associated with the main river crossing.

Due to the lengthening of the spans, the depth of the deck section was increased from 16 ft proposed in the amended 2010 VQM concept to 18 ft. Selection of the deck section was an

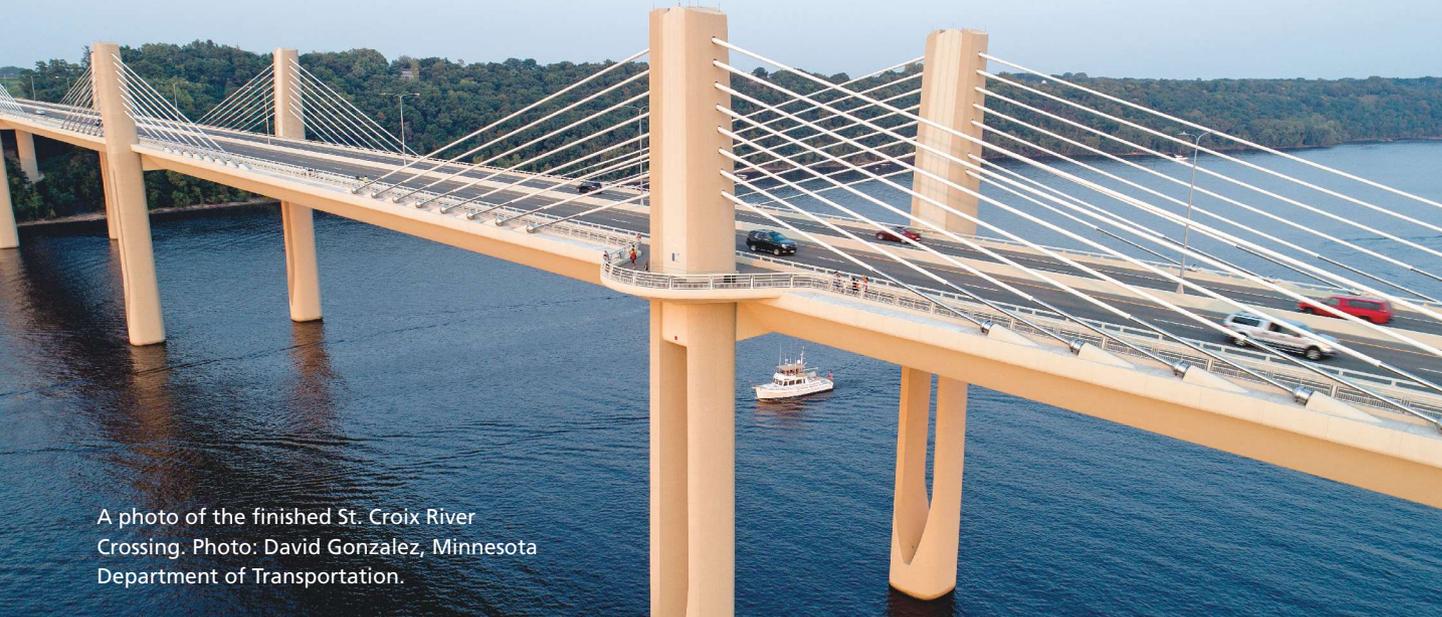
important consideration for the final design. Schedule and constructability were paramount considerations. Precast concrete segmental construction was selected over cast-in-place construction to minimize the construction schedule and project costs. To match the precast concrete segmental schedule, cast-in-place construction would have required several large form travelers working in difficult weather conditions. The selection of the precast concrete segmental option led to a twin box-girder arrangement instead of a single box-girder design because the former would minimize weight for segment handling. Additionally, the twin box-girder arrangement allowed deck drain pipes to travel down the middle of the bridge external to the box girders, a feature that was important to MnDOT, which had encountered problems with drain pipes leaking inside box girders on previous projects.

Three twin box-girder concepts were studied during the development of the final design: twin three-cell boxes, twin strutted boxes, and twin two-cell boxes. All three deck sections have a cast-in-place closure joint between the box girders and a strutted connection at the bottom flange level. The limited width of the bottom flange of the two-cell box was ultimately not viable because of the large hogging demands at the piers and the large quantity of post-tensioning tendons in the bottom flange required at midspan. The heavier three-cell box section was considered more constructable and resilient and was therefore selected.

The extradosed cable-stays largely provide longitudinal post-tensioning to the deck section; however, they also provide some vertical support to the outside edge of the wide deck section. The twin box girders with their central cells behave essentially as Vierendeel frames in the transverse direction. To distribute the vertical support from the extradosed stay-cables effectively across the deck section, external transverse post-tensioning tendons are located at each stay-cable anchorage. The tendons are deviated at the inner web of the three-cell box to transfer vertical load to the inner girder web, which would otherwise rely on transverse Vierendeel effects to take up vertical load from the



Single box-girder and twin box-girder design concepts for bridge as considered in 2010. Figure: Minnesota Department of Transportation.



A photo of the finished St. Croix River Crossing. Photo: David Gonzalez, Minnesota Department of Transportation.

stays. The transverse tendons also act to post-tension the struts connecting the bottom flange of the twin box girders and to deviate the horizontal cable force into the deck section.

Considerable effort was put into refinement of the pier and pylon shapes in the final design stage. The efforts were focused on both the visual aspects of the pylons and structural efficiency. The twin legs beneath the pier crossbeam were widened and thinned to obtain the necessary cross-sectional area to carry the vertical loads while at the same time reducing the moment of inertia of the legs to minimize force effects generated from longitudinal thermal and time-dependent length effects in the deck. This design modification was particularly critical for pier 8, which, as a result of the grade on the bridge, is the shortest and stiffest of the piers and therefore attracts the largest forces.

To maintain constructability as well as the visual theme for the piers, the vertical edges were curved with dimensional variations made only to the tangents connecting the curves. Texture given to the outside face of the upper pylon eliminates what would otherwise be a large, flat surface, thereby adding visual interest—particularly when the bridge is lit at night.

Internal steel anchor boxes are used in the upper pylons to anchor the stays and resist the large tensile splitting force generated by opposing pairs of extradosed cable stays. In the 2007 and 2010 design concepts, the pylons above the deck were visualized as relatively monolithic in form. In the final design, the above-deck pylons are tapered, which gives the structure a pleasingly slender and open appearance from the perspective of the motorists, bicyclists, and pedestrians who cross the bridge.

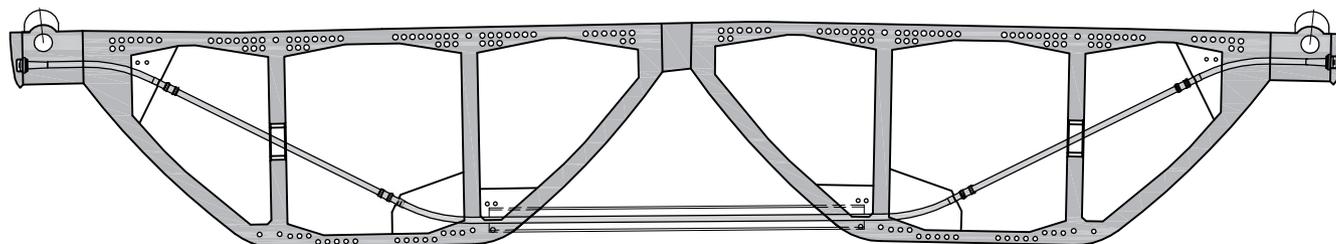
## Design of the Segmental Box-Girder Approaches

### Mainline Approach

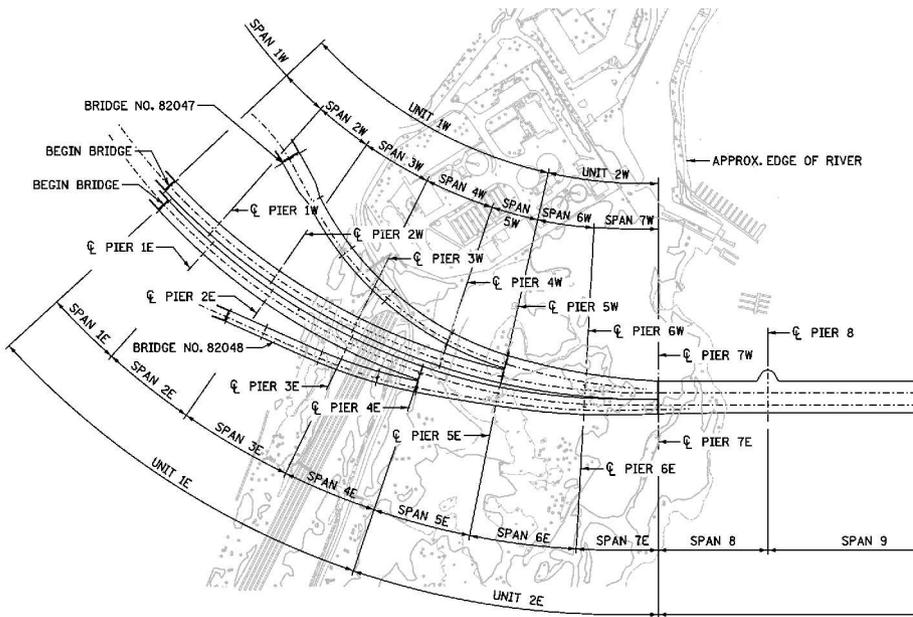
In addition to the previously described changes in the extradosed structure, the design team also refined the preliminary design of the mainline, off-ramp, and on-ramp approach structures. The 2007 preliminary plans included a sag curve located approximately halfway down the mainline approach and a horizontal curve with associated superelevation, which extended into the second span of the extradosed structure. The on- and off-ramps originally extended further to the east, with the transition also extending into the second span of the extradosed structure. The mainline approach was composed of twin

boxes connected with a longitudinal joint. These features caused a very wide twin box structure, and, with a 6% superelevation, the south side of the bridge would extend upward a significant distance to provide sufficient vertical clearance over Minnesota Trunk Highway (TH) 95. The low point on the bridge for drainage was located at midspan, causing significantly large longitudinal drainage pipes.

The revised 2010 mainline approach design consisted of two units with twin box-girder superstructures. The joint between the two structures was at the confluence with the on- and off-ramps. The box girders were separated with offset horizontal alignment and twin vertical curves to form unit 1. The twin box girders were then brought back together, forming unit 2, with a longitudinal joint before the pier 8 transition to the extradosed unit 3. This allowed the vertical curve to be moved west and the horizontal alignment to be modified, bringing the superelevation transition onto the approach bridge and off the extradosed span. The designers were then able to shift the on- and off-ramps further west, greatly reducing the widening of the extradosed end span. This change also moved the low point of the bridge to pier 1 on the off-ramp, which reduced the size of the



Typical cross section at anchorage locations of main cable showing transverse external post-tensioning and strut between boxes. Figure: Minnesota Department of Transportation.



Plan layout of the extradosed St. Croix River Crossing. Figure: Minnesota Department of Transportation.

trunk line for the drainage system. The end result produced a twin box-girder system for unit 2, which was a significant improvement over the complex framing system envisioned in 2007.

The final design for the mainline approach consists of four separate units: units 1 and 2, east and west. Both units 1 and 2 are composed of continuous spans of post-tensioned box girders, with the unit 1 box girders being precast concrete segments erected using balanced-cantilever method and unit 2 box girders constructed with cast-in-place concrete on falsework. Piers for both units are founded on steel HP piles.

Unit 1E is a 964-ft 3-in.-long, four-span bridge that carries eastbound TH 36. It has two 12-ft-wide traffic lanes, a 6-ft-wide inside shoulder, and a 10-ft-wide outside shoulder. The out-to-out bridge width is 43 ft 4 in. The single box girder varies in depth from 10 ft at pier 1 to 14 ft at the beginning of pier 2. The four-span continuous structure has modular expansion joint devices located at abutment 1 and pier 4E, expansion bearings at abutment 1 and piers 1E and 4E, and fixed-bearing connections at piers 2E and 3E.

Unit 1W is a 1212-ft-long, five-span structure that carries westbound TH 36 using the same roadway cross section as unit 1E. The five-span continuous structure has modular expansion joint devices located at abutment 1 and pier 5W; expansion bearings at abutment 1

and piers 1W, 4W, and 5W; and fixed-bearing connections at piers 2W and 3W.

Unit 2E is a 749-ft 9-in.-long, three-span structure in the gore area where the on-ramp merges with mainline eastbound TH 36. The out-to-out bridge width varies from 82 ft 6 in. to 46 ft 7 in. The box girder varies in depth from 14 ft at pier 5E to 18 ft at the beginning of pier 6E. The three-span continuous structure has modular expansion joint devices located at piers 4E and 7E, expansion bearings at piers 4E and 7E, and fixed-bearing connections at piers 5E and 6E.

Unit 2W is a 488-ft-long, two-span structure in the gore area where the off-ramp departs from mainline westbound TH 36. The out-to-out bridge width varies from 88 ft 3 in. to 55 ft 10 in. The box girder varies in depth from 14 ft at pier 5W to 18 ft at the beginning of pier 6W. The two-span continuous structure has modular expansion joint devices located at piers 5W and 7W, expansion bearings at piers 5W and 7W, and a fixed-bearing connection at pier 6W. Additionally, there is one more span with a conventional pier (pier 13) after the last extradosed pier (pier 12). This section is part of the extradosed structure and not a separate approach bridge or span.

### Off-Ramp Approach

The off-ramp approach is a five-span bridge composed of a 960-ft 11-in.-long, post-tensioned single box-girder structure. The bridge is the off-ramp from westbound TH 36 and carries

one traffic lane, two auxiliary lanes to pier 1, 4-ft-wide shoulders, and a 12-ft-wide, barrier-separated trail. The out-to-out bridge width varies from 60 ft 6 in. to 40 ft 6 in. The box girder varies in depth from 10 ft at pier 3 to 14 ft at the beginning of pier 4. The bridge was constructed with precast concrete segments erected using the balanced-cantilever method. The five-span continuous structure has modular expansion joint devices located at abutment 1 and pier 5; expansion bearings at abutment 1 and piers 1, 2 and 5; and fixed-bearing connections at piers 3 and 4.

### On-Ramp Approach

The on-ramp approach is a four-span bridge composed of a 632-ft 11-in.-long, post-tensioned single box-girder structure. The bridge is the on-ramp to eastbound TH 36 and carries one traffic lane and one auxiliary lane with 4-ft-wide shoulders to pier 3. The out-to-out bridge width is 35 ft 4 in. The box girder varies in depth from 10 ft at pier 2 to 14 ft at piers 3 and 4. The bridge was constructed with cast-in-place concrete

### A Firsthand Account by Fredrick Gottemoeller

When viewing this bridge from upstream or downstream, you can't help but be impressed by the degree to which the structure seems to disappear into the landscape. The hillsides and sky beyond can be clearly seen through the vertical slots in the piers, and the sides of the piers look like the stalks of aquatic reeds, just as the authors of the visual quality manual envisioned. The curved surfaces of the piers and girders not only seem "organic" but also make it difficult to judge the actual dimensions of the piers and girders, thus minimizing their visual mass.

These curved shapes continue smoothly into the girders and piers of the Minnesota interchange. All transitions in girder depth are accomplished with gradual tapers. The interchange piers borrow shapes and details from the river piers. Whether crossing below the approaches on the highway or proceeding down the St. Croix River on a dinner cruise, onlookers will enjoy the strongly articulated, unified vision of the bridge's integrated design.

on falsework. The four-span continuous structure has modular expansion joint devices located at abutment 1 and pier 4; expansion bearings at abutment 1 and piers 1 and 4; and fixed-bearing connections at piers 2 and 3.

### Design Criteria, Materials, and Post-Tensioning

The bridge was designed for a 100-year service life. The following were used to increase the durability and service life of the bridge:

- Stainless steel reinforcement in the top deck of the box girder with a zero-tension limit on the top fibers.
- Epoxy-coated reinforcement in the rest of the box-girder superstructure and in the substructure above the footings.
- Post-tensioning, both longitudinally and transversely, to limit concrete tensile stresses.
- Thixotropic grouts (see the related Concrete Bridge Technology article in this issue).

### References

1. Minnesota Department of Transportation (MnDOT). 2006. *St. Croix River Crossing Supplemental Final EIS*. <http://www.dot.state.mn.us/metro/projects/stcroix/pdfs/sfeis2006/Chapters%20and%20Figures/Ch7/StCroixSFEIS-Ch7.pdf>.
2. Parsons Brinckerhoff. 2010. *St. Croix River Crossing Project Visual Quality Manual Addendum: Final Submission*. Prepared for MnDot and Wisconsin Department of Transportation. <http://www.dot.state.mn.us/metro/projects/stcroix/pdfs/vqalow-res.pdf>. 

*Craig Lenning is senior vice president for HDR in Minneapolis, Minn. Don Bergman is vice president and senior project director COWI Bridge for COWI North America Ltd in North Vancouver, BC.*

#### EDITOR'S NOTE

*For more details on the grouting of post-tensioning tendons for this project, see the Concrete Bridge Technology article on pages 34-36 in this issue. For a time-lapse video of the construction of the St. Croix River Crossing, please see <https://www.youtube.com/watch?v=iexen6Csef0>. Video courtesy of EarthCam.*



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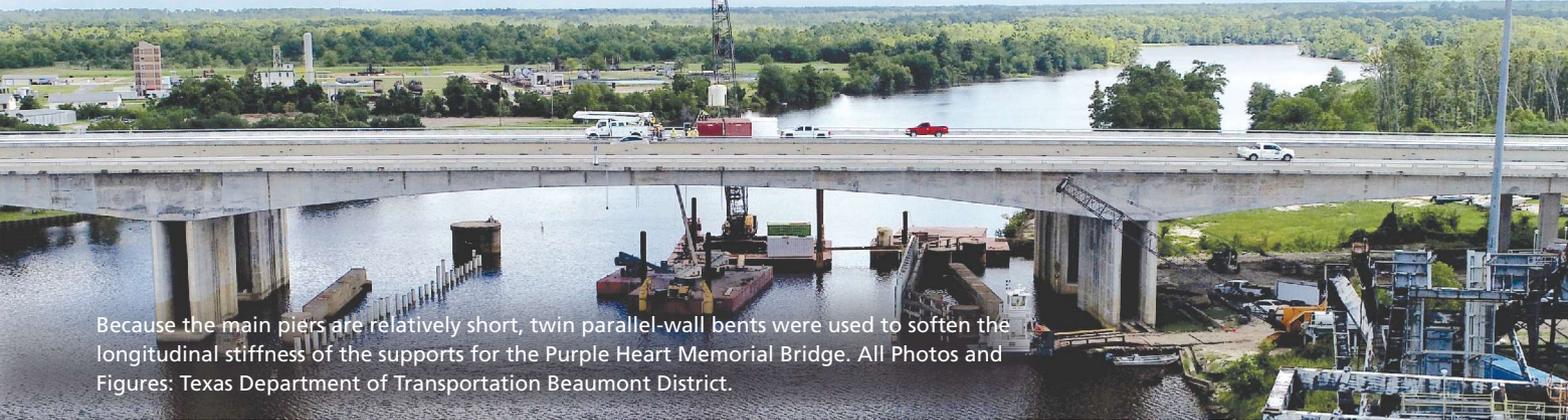
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## PROJECT

# Purple Heart Memorial Bridge over the Neches River

by Kenneth Wiemers, Texas Department of Transportation, Amy Smith, HDR, and Tom Stout, Stantec



Because the main piers are relatively short, twin parallel-wall bents were used to soften the longitudinal stiffness of the supports for the Purple Heart Memorial Bridge. All Photos and Figures: Texas Department of Transportation Beaumont District.

Built from 1952 to 1953, the second Interstate 10 bridge crossing the Neches River in Beaumont, Tex., was a marvel of slide-rule engineering and built-up, riveted steel plate girder construction. Unfortunately, it had a subtle flaw. When the bridge was widened in 1976, the longitudinal slab construction joint was placed directly over the original outside girder. The original 6¼-in.-thick slab was placed in 20-ft segments with transverse construction joints between segments; however, no longitudinal reinforcement connected the segments. Although the 1976 plans showed that the existing transverse reinforcement would be cleaned and straightened into the new construction, results over time showed that this detail may not have been followed.

By 2000, the Texas Department of Transportation's (TxDOT's) maintenance forces were out on the deck almost

monthly to patch the slab punchouts occurring at those corners between the longitudinal construction joint and the original deck segments. The time had come to evaluate other options. Redecking the bridge was considered; however, as the old deck was removed, suspected disintegration of the top flange of the original exterior girder under the leaking longitudinal construction joint was confirmed. TxDOT did not want to assess and then possibly repair 3450 ft of girder on this extremely busy and important corridor, so it decided to replace the old bridge with concrete girder approaches and segmental main spans.

### Project Specifications

Whereas the old bridge was a single structure, the new crossing consists of eastbound and westbound twin structures, with just a 1-in.-wide gap at the roadway tie-ins and a 12-ft-wide separation at the segmental portion. The

twin-structure design was selected for the Purple Heart Memorial Bridge for traffic control and inspection reasons. Each new structure is 70 ft wide and carries four lanes of traffic. There are 23 approach spans of prestressed concrete girders flanking the three-span balanced-cantilever segmental main unit over the Neches River.

Despite being more than 35 miles inland from the Gulf of Mexico, the Neches River is navigable under the bridge. Therefore, U.S. Coast Guard clearances had to be provided. The previous bridge had a main span of 240 ft and, because the alignment of the new Purple Heart Memorial Bridge was over the old bridge, the new main span had to extend beyond the existing piers. A balanced-cantilever segmental bridge proved to be the best choice for the main unit, ultimately providing 193 ft of horizontal navigation clearance.

## profile

### PURPLE HEART MEMORIAL BRIDGE / BEAUMONT, TEXAS

**BRIDGE DESIGN ENGINEER:** Texas Department of Transportation, Austin, Tex.

**PRIME CONTRACTOR:** Williams Brothers Construction Company, Houston, Tex.

**PRECASTER:** Valley Prestress Products, Eagle Lake, Tex.—a PCI-certified producer

**POST-TENSIONING CONTRACTOR:** Williams Brothers Construction Company, Houston, Tex.

**OTHER MATERIAL SUPPLIERS:** Formwork, form travelers, and erection equipment: Williams Brothers Construction Company, Houston, Tex.; reinforcement fabricator: CMC Steel, Seguin, Tex.; bearings: Seismic Energy Products, Athens, Tex.; expansion joints: CMC Capital City Steel, Buda, Tex.; post-tensioning ducts and anchors: DYWIDAG-Systems International, Mansfield, Tex.; and post-tensioning steel: Insteel Wire Products, Gallatin, Tenn.

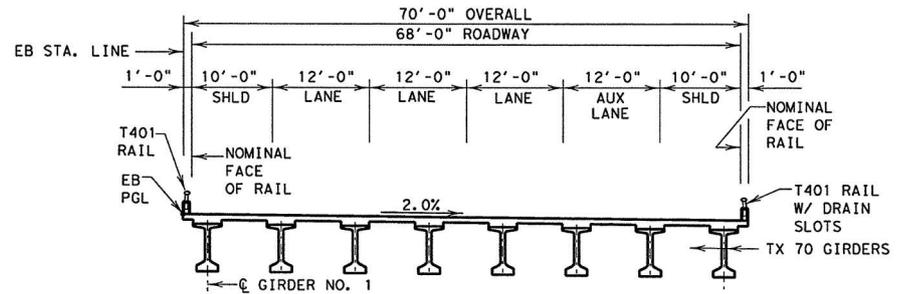
## High-Performance Concrete

The Texas Department of Transportation's standard specification for producing high-performance concrete offers several options. However, in Texas, Class F fly ash is almost always included within the concrete. The result is a low-cost, highly durable, and low-permeability concrete.

For this project, the following compressive strength performance requirements were specified:

- 3.5 ksi prior to removing the forms
- 4.0 ksi before post-tensioning the top slab longitudinal and transverse tendons
- 5.5 ksi before post-tensioning the bottom longitudinal tendons
- 6.0 ksi at 28 days

The design team selected cast-in-place construction using form travelers for the segmental units. Using cast-in-place concrete was preferable over precast concrete construction for a few reasons. Because the bridge is adjacent to downtown Beaumont, there would have been little available



Typical cross sections for Tx70 girder approaches and segmental box-girder main spans of eastbound bridge (spans 13–16 and 20–26).

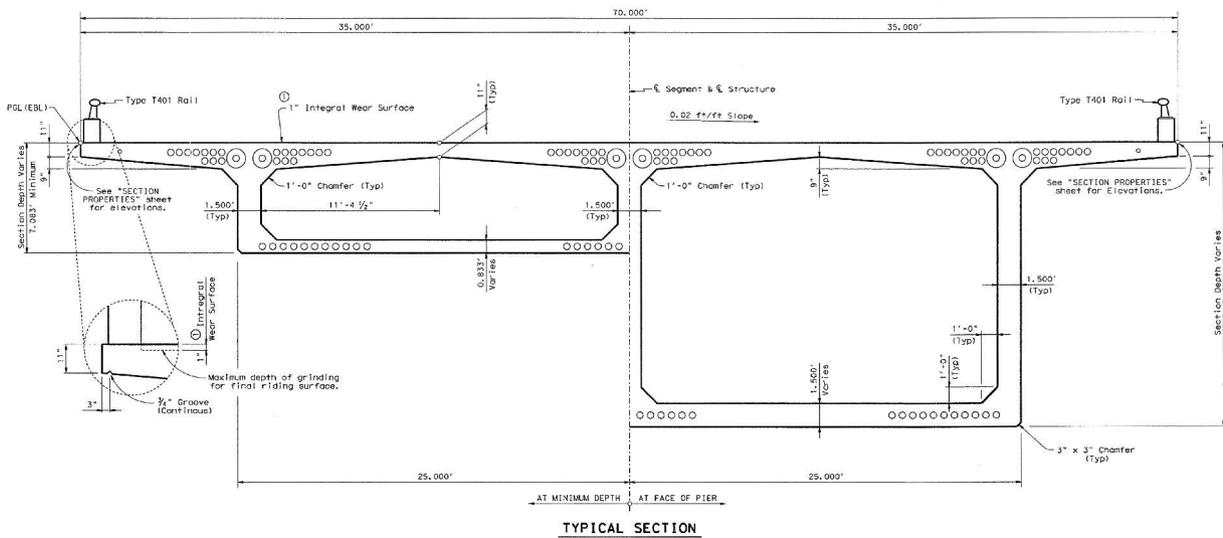
space to set up a staging and lifting yard for precast concrete segments. Also, the bridge crosses the Neches River at a location with numerous environmental challenges; therefore, launching precast concrete segments from a barge would have added a great deal of complexity and expense to the project. Furthermore, much of the cost savings associated with using precast concrete would not have been realized because the project has only six spans.

The segmental main units have spans of 180, 320, and 180 ft. The 70 ft deck

width was achieved with a double-celled box. The parabolic soffit varies in depth from just over 7 ft at midspan to 18 ft at the piers. The webs are 18 in. thick, and the thickness of the bottom slab varies from 10 to 18 in. Tendons consist of eleven 0.6-in.-diameter strands in both the top and bottom slabs.

Forty-three segments were cast for each structure. To keep unbalanced moments to a minimum, the pier table was cast with one side half a segment longer than the other. Therefore, as each segment was constructed out from the pier on alternating sides, the

Typical section for concrete segmental box-girder main span unit. Left side shows minimum depth section (7 ft 1 in.); right side shows maximum depth section at face of pier (18 ft 1 in.).



## TEXAS DEPARTMENT OF TRANSPORTATION, OWNER

**BRIDGE DESCRIPTION:** Twin bridges, each with a total length of 3895 ft, consisting of a three-span post-tensioned cast-in-place segmental concrete box-girder main unit (180, 320, and 180 ft) and 23 approach spans of prestressed concrete girders

**STRUCTURAL COMPONENTS:** 70-ft-wide cast-in-place balanced-cantilever constructed double-cell segmental box girder with depths varying from 7 ft to 18 ft; 8-in.-thick deck on 70-in.-deep bulb-tee prestressed concrete girders for approach spans (maximum 152 ft); 4-in.-thick precast, prestressed concrete deck panels; cast-in-place pier caps supported by columns and column walls; and 18-in.-square precast, prestressed concrete piles approximately 70 ft in length

**BRIDGE CONSTRUCTION COST:** \$68 million (\$124/ft<sup>2</sup>)



Tx70 bulb-tee girders have been set for the eastbound approach spans on the Orange County side of the river.

system would never be more than a half segment out of balance. Five access doors are provided at each pier table for easy access to the various sections of the bridges for inspections. Future post-tensioning needs are addressed by the inclusion of empty

ducts in the shear walls in both the pier table and end anchor segments.

Because the main piers are relatively short (approximately 38 ft off the water), twin parallel-wall bents were used to soften the longitudinal stiffness of the supports, thus keeping temperature-induced moments from driving the segmental design. The walls rest on a twin-cell hollow column from the waterline down to the 51 × 38 × 8 ft pile cap. Each main pier is supported on ninety approximately 70-ft-long, 18-in-square precast, prestressed concrete piles.

Like all segmental bridges constructed in Texas, the Purple Heart Memorial Bridge includes concrete pavement ride requirements. For this bridge, the plans required 3 in. of concrete clear cover, which provided sufficient thickness for the contractor to diamond grind the pavement to satisfy the ride specification while also maintaining sufficient cover for the deck reinforcement.

The approach spans consist of Tx70 bulb-tee prestressed concrete girders (70 in. deep); this project was the first

to use this particular shape. This type of girder has proven to be extremely stable, and it, as well as the other bulb-tee girder shapes developed by TxDOT, are now used frequently throughout the state. The lengths of the Purple Heart Memorial Bridge approach spans vary, reaching a maximum of 152 ft. No continuity other than the deck slab was provided, and the girders were designed as simple spans. Precast, prestressed concrete subdeck form panels were used throughout the approach spans, as is the usual practice in Texas.

These side-by-side, 3896-ft-long structures used prodigious amounts of concrete:

- 478,000 ft<sup>2</sup> of approach bridge deck
- 57,000 linear ft of prestressed concrete girders
- 16,000 linear ft of bridge rail
- 13,000 yd<sup>3</sup> of approach bent high-performance concrete (HPC)—see the sidebar for more information on the HPC
- 2500 yd<sup>3</sup> of main pier HPC
- 10,500 yd<sup>3</sup> of concrete in the segmental bridge



Completed pier table on twin parallel-wall columns for segmental box-girder main span unit.

## Location-Related Challenges

Because very little right-of-way was acquired, the old bridge had to be deconstructed in phases to allow the new eastbound bridge to be built while maintaining traffic. The deconstruction plan represented its own complex project, with 54 plan sheets dedicated to propping up the old structure long enough to build the new one. Because the old slab was in such poor condition, 440,000 pounds of rolled girders were needed to shore the slab edge.

Equally as challenging as the actual design were the ancillary issues addressed in the design process. A bathymetric survey done to gauge the condition of the river bottom uncovered a sunken World War I-era wooden steamship lying up against the pivot pier of the original swing bridge at this crossing. According to contemporaneous newspaper reports, the 286-ft-long vessel had caught fire at its moorings in 1924 and drifted downstream to bump into the newly completed swing bridge, where the ship eventually sank. After coordinating with the Texas Historical Commission, a no-disturbance zone was delineated in the plans along with a monitoring system as a means of preventing damage to the wreckage during construction of the new bridge.

Brakes Bayou, on the west side of the river system, was home to an Environmental Protection Agency Superfund site. Remediation to clean up a former creosote plant was ongoing, and disturbance of the sediment at the bottom of the bayou had to be kept to a minimum. Turbidity barriers were installed during the driving of the concrete piles to capture silt. Pile caps that would have normally been placed below the mudline were instead left at the normal water elevation.

Another environmental concern was that the existing steel girders in all spans were known to have lead in their paint coating. Therefore, to ensure that the contractor could safely make cuts in the beams, a separate contract was arranged for the removal of the paint at specific locations before the beginning of construction.

The old bridge conveyed numerous utilities across the river. Because of phasing constraints, the owner decided to not include space for them on the new bridges. Instead, the utilities were relocated to a common bore under the river at a location away from the bridge.

## Conclusion

Bridges over time become part of the historical landscape of the community they serve. The new Purple Heart Memorial Bridge is the third generation of structures to inhabit this site. The previous bridges are woven into the fabric of Beaumont, Tex., even if all that is now visible are a few abandoned piers, shorn to the waterline. We hope the new bridges add to that legacy of silent service, transporting generations of families toward their futures. **A**

*Kenneth Wiemers is the Texas Department of Transportation area engineer in Beaumont, Tex. Amy Smith is a senior bridge engineer for HDR Inc, in St. Louis, Mo. Tom Stout is a bridge designer for Stantec in Austin, Tex. Both Smith and Stout were formerly with TxDOT.*



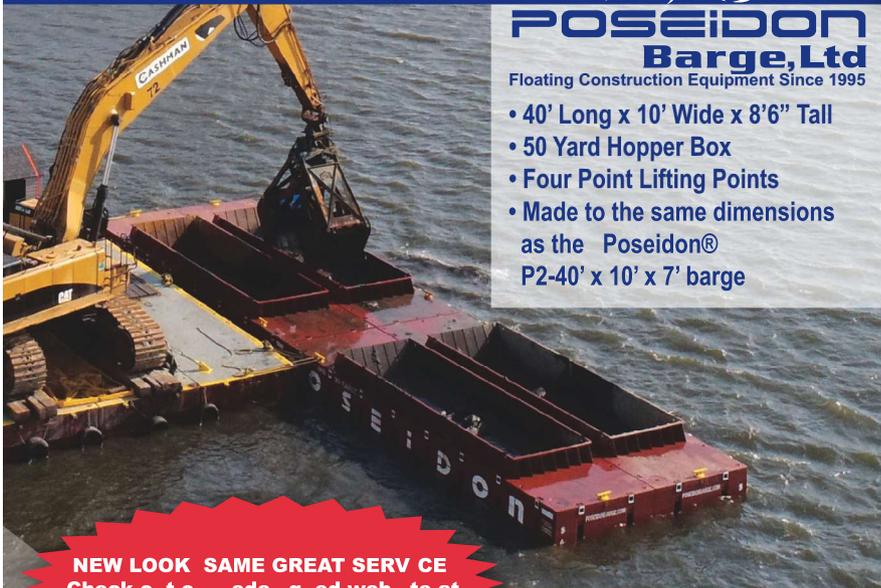
Cantilever truss being set up to make the segmental closure pour on the eastbound side of the Purple Heart Memorial Bridge at its connection to the precast concrete girder approach portion. Bearing seat buildups are on the right, and metal overhang and bottom forms are in the center. Post-tensioning ducts and grouting ports can be seen as well as the cavities of the double-celled box segments.

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## A Unified Approach to Seismic Analysis, Design, and Detailing of Prestressed Concrete Piles

by Dr. Timothy W. Mays, The Citadel

Seismic analysis, design, and detailing provisions for piles used to support building structures are very different than those for piles supporting bridge and pier superstructures. The main difference involves the expected performance of piles during the design earthquake, as reflected by the overall pile behavior philosophy mandated in the codes governing the design of these two types of structures.

For building structures, standard practice considers the pile foundation system to be the fixed-base portion of a structural model, and the foundation design is governed by reactions at the base of the above-ground structure at or near the pile head. Pile foundation forces for buildings are based on lateral forces obtained using code-prescribed response modification coefficients ( $R$  values) for the building's specific lateral force-resisting system. (For buildings, it is assumed that all damage takes place above grade). Additional prescriptive deflection limits and other criteria are intended to ensure an elastic response of the building piles. Contrary to the anticipated elastic pile behavior described above, and as an additional measure of conservatism, prescriptive detailing provisions for building

piles result in ductile capacities that approach those for columns in special reinforced concrete moment frames.

In bridge and pier structures, the piles are often considered to be the structure's lateral-force-resisting system. In fact, response modification coefficients are provided in the bridge and pier codes for these applications, but  $R$  values are not provided for piles in building applications because building piles are not permitted to be elements of a lateral-force-resisting system. In addition, bridge and pier codes encourage performance-based seismic design of piles that includes or allows for pile hinging and controlled pile damage. Performance-based seismic design of piles involves detailing the needed (not prescriptive) amounts of spiral reinforcement and providing this reinforcement only where needed as based on soil-structure interaction modeling, appropriate consideration of head fixity, and other design considerations.

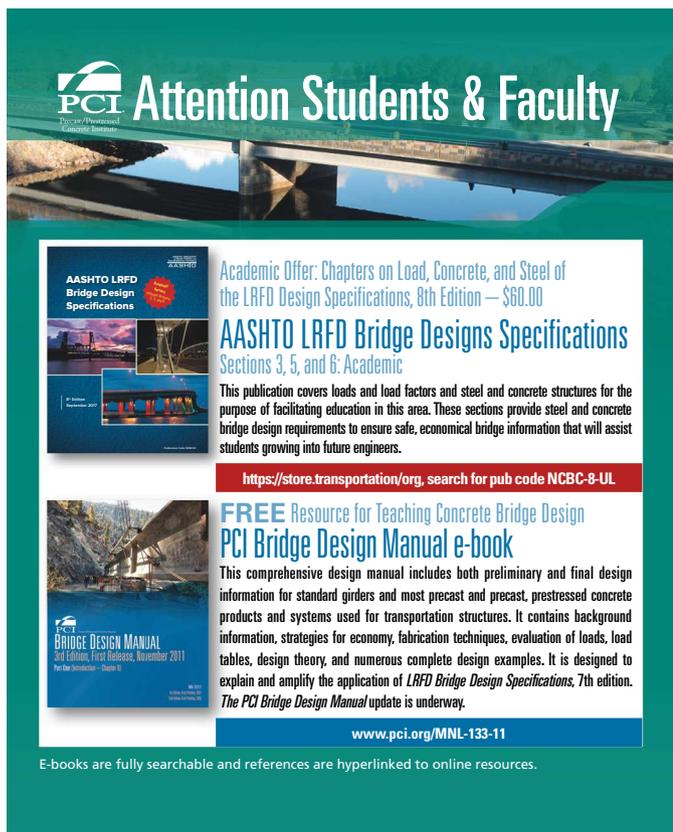
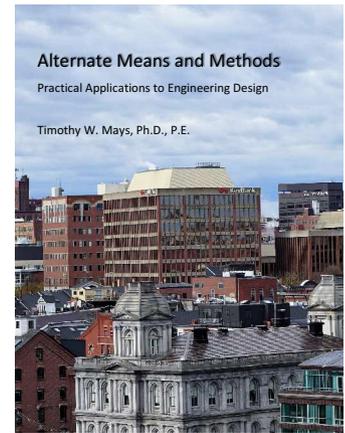
Education courses based on the new book *Alternate Means and Methods: Practical Applications to Engineering Design* are currently being presented by Structural Engineers Association chapters in various cities in the southeastern United States. This book, which goes into great detail about a variety of practical solutions to complicated problems in the building industry, includes a special section on prestressed concrete pile design with an example building that uses piles with stick-up as part of a building's lateral-force-resisting system. Most recently, on the campus of The Citadel in Charleston, S.C., a related presentation was given to the local chapter of the Pile Driving Contractors Association on how a unified approach to prestressed concrete pile design leads to significant economic benefits (10% to 30%, or more, in overall material cost savings) while also offering the design engineer a more reliable load path and a better understanding of how the pile system will respond to the design earthquake.

The Precast/Prestressed Concrete Institute is leading an effort to unify prestressed concrete pile provisions for all structures. The approach will allow for both traditional prescriptive design and performance-based design of piles. Special analysis, design, and detailing provisions will also be provided, depending on whether the piles are being considered as part of the structure's lateral-force-resisting system (that is, whether controlled pile damage is being permitted as part of the overall structural seismic response). 

*Dr. Timothy Mays is a professor in the Department of Civil and Environmental Engineering at The Citadel in Charleston, S.C.*

### EDITOR'S NOTE

For more information regarding these training sessions, please contact Dr. Mays at [mays1@citadel.edu](mailto:mays1@citadel.edu)



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## PROJECT

# SECOND STREET BRIDGE OVER THREE-MILE CREEK

by Michael McDonald, City of Leavenworth, Kans., and Lindsay Madsen, TranSystems

The new single-span adjacent precast, prestressed concrete box-beam bridge with the shared-use trail beneath. All Photos and Figures: TranSystems/City of Leavenworth.

Originally built in 1915, the Second Street Bridge over Three-Mile Creek in Leavenworth, Kans., was the last remaining original concrete arch crossing the creek. It was slated for rehabilitation in 2008, but inspection found extensive damage and so it became eligible for replacement. The project replaces the 50-ft-long concrete arch structure and includes reconstruction of Second Street to the north and south of the bridge.

Leavenworth is a town of about 35,000 people and home to Fort Leavenworth, which was a key supply base in the settlement of the American West and is currently a major military installation. Second Street is a main road in the downtown area, with an average daily traffic of 1100 vehicles. Residents rely on this throughway to connect them between downtown and residential areas. Construction for this project began in May 2017, and the new bridge opened

to traffic October 2017. The schedule was aggressive due to the constraints of when and how long the utilities crossing Three-Mile Creek were allowed to be shut down. To meet heating demands, the gas line could not be shut off until May and had to be operational by October. The bridge also crosses over a shared-use trail, and it carries traffic from Leavenworth Landing Park into the heart of downtown, a historic area close to the Missouri River that is being revitalized by private development and city infrastructure projects.

### Advantages of Precast Concrete Box Beams

Initially, the City of Leavenworth intended to replicate the original arch-type structure in the new bridge. However, because of the small footprint of the project, geotechnical limitations, and funding constraints, that plan could not be implemented. Still, the designers kept the aesthetics of the original bridge in mind. Ultimately, a single-span structure with adjacent precast, prestressed concrete box beams was selected. The new structure maintains

The new railing has a similar aesthetic pattern to that of the former arch bridge.

## profile

### SECOND STREET BRIDGE OVER THREE-MILE CREEK / LEAVENWORTH, KANSAS

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

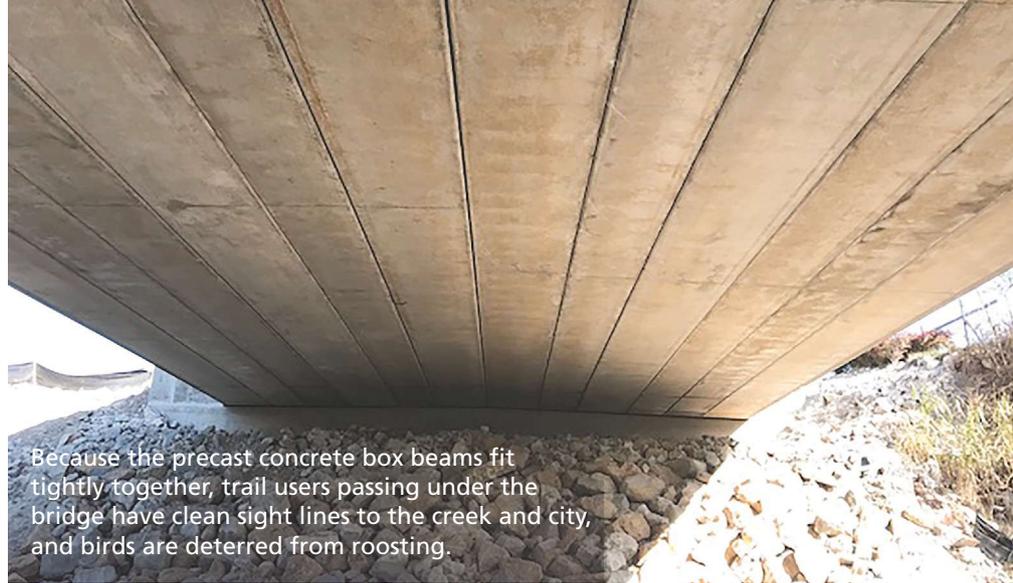
**PRIME CONTRACTOR:** L.G. Barcus and Sons, Kansas City, Kans.

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

the clean profile and alignment of the bridge it replaces. The beams of the bridge fit tightly together so as to not distract from the scenic surroundings, and the concrete box girders placed side by side create a pleasing appearance for the trail users below. Box girders placed tightly also prevent birds from roosting on the bridge, which limits droppings on the trail.

Adjacent box beams allow for a thin deck (a minimum depth of 5½ in.), as well as a taller curb and sidewalk, which added additional dead load. The exterior faces of the box beams are flush with the aesthetic barrier rail to mimic the taller, detailed railing on the old arch. Lighting will be added to resemble the same lighting features from the early days of the arch bridge.

The cost savings of using precast, prestressed concrete box beams fabricated less than 30 miles away from the project site were one reason why this material was selected instead of steel beams or traditional concrete I-beams. Also, precast concrete box beams were preferred over traditional concrete I-beams because the geometry of the box beams allowed for more flexibility of the beam shape and size



Because the precast concrete box beams fit tightly together, trail users passing under the bridge have clean sight lines to the creek and city, and birds are deterred from roosting.

to better meet the needs of the project, which ultimately used two different widths of beams. Another advantage of using precast concrete box beams was the ability to replicate the uniform color of the original structure. Plus, concrete facades require significantly less maintenance than steel ones—painted steel often needs repainting while this concrete will not.

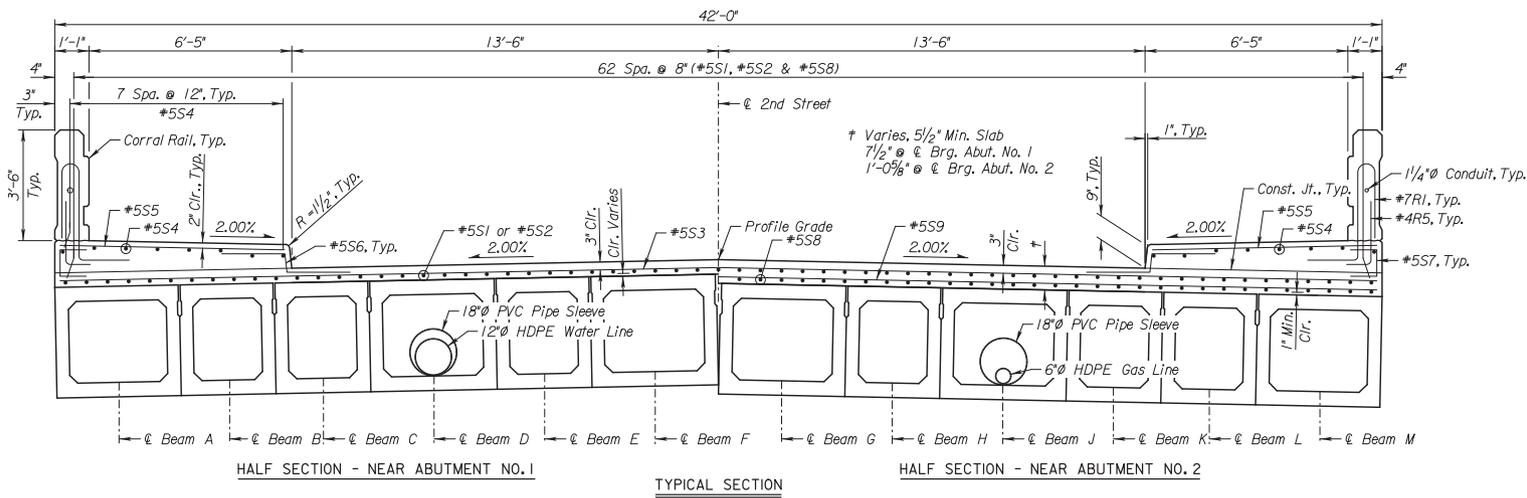
portion of the adjacent property could not be excavated unless a lengthy, extensive, and expensive investigation was performed. The owner therefore directed the design team to avoid all subsurface use of that property.

Utility relocation was another issue that had to be addressed. Three utilities cross Three-Mile Creek at this location: electricity, water, and natural gas. The high-voltage transmission line could be shut off during construction, but it could not be relocated. The contractor was limited to a 15-ft minimum clearance from the overhead power lines for all work. Also, to meet summer

### Physical Project Challenges

Many physical challenges were encountered during the Second Street Bridge project. One was the constrained project site. Because of potential contamination issues, a

Typical section of the 42-in.-deep precast, prestressed concrete box-beam bridge.



## CITY OF LEAVENWORTH, KANSAS, OWNER

**BRIDGE DESCRIPTION:** Simple-span, 119-ft-long bearing to bearing adjacent precast, prestressed concrete box-beam bridge

**STRUCTURAL COMPONENTS:** Twelve beams: six 42-in.-deep AASHTO Type BIV-36 concrete box beams and six 42-in.-deep AASHTO Type BIV-48 concrete box beams (two of which have 18-in.-diameter PVC pipe sleeves for utilities); 5½-in.-minimum cast-in-place concrete deck; cast-in-place concrete abutment pile caps; and concrete-encased H-piles

**BRIDGE CONSTRUCTION COST:** \$1,547,523

**AWARD:** 2018 APWA Kansas City Metro Chapter Public Works Project of the Year Award-Small Communities

cooling demands, the power lines could not be de-energized once the air temperature was more than 80°F. This requirement limited the working time in the summer months.

The water and natural gas mains were more of a challenge than the power lines. The construction time frame was constrained by when gas could be turned off. While the natural gas main was to be removed during construction, it had to remain in service until April 1 and be reinstalled and operational by October 1 to meet heating demands. Although the time frame for the water main was not as restrictive, it was to be shut off and resume operations within the same timeline as the gas main.

The design team worked with the precaster and utility companies to design an interior framework to support utilities within the voids of the box beams. By routing the water- and gas-main lines through the voids, the team avoided boring under the creek, which would have been costly and time consuming and would have exposed the utilities to possibly unstable subsurface conditions. Routing the utility lines through the box beams kept the mains on their original alignment while concealing them, providing a cleaner look for the new bridge and eliminating places for animals to hide and cause a nuisance to trail users. This solution also allowed the team to work within the tight time frame to make the utilities operational again. This project is the first time in Kansas that utilities have been routed through the voids of a box-beam structure of this length.

### Creative Use of Resources

The foundations of the original arch bridge remain in place as retaining walls along Three-Mile Creek, thereby providing a simple design for the new abutments outside the creek waterway and minimally disrupting the creek banks. This reuse and repurposing of the original foundations and adjacent retaining walls saved money and construction time. By leaving the lower 8 ft of the existing walls in place, a more open crossing of Three-Mile Creek was achieved while offering a reminder of what the previous structure looked like. The soils along one bank were found to likely be contaminated, and those on the other bank were of questionable use as fill material. By repurposing the original arch foundation, environmental challenges were avoided, aesthetics were improved, and a significant amount of money was saved.

Other unique site elements contributed to modifications in the design. Information about the old structure's foundation was scarce, which is not unusual for a century-old bridge. In this case, the lack of information proved to be a challenge in construction. During excavation for the abutments, counterforts for the existing wing walls were discovered. These counterforts interfered with the placement of the new abutment cap and piling. On-site modifications were discussed, and an adjustment was engineered to avoid the conflict.

The south abutment was designed to be supported on driven H-piles set into shale, but a rock shelf was encountered roughly 15 ft higher than expected,

even with two borings within 20 feet of the shelf. The H-piles were quickly redesigned as concrete-encased H-piles set into the shale and limestone, with a final elevation 15 ft above the original design. Reuse of the old foundations and new abutments placed outside of the creek reduced the complexity of the permitting required from both the State of Kansas and the Corps of Engineers.

Another unique aspect of the construction process was the setting of the precast concrete box beams. The box beams were 120 ft long, and the transporting trucks had to back through a residential neighborhood. Setting the beams was difficult because of the proximity of adjacent buildings, overhead power lines, and the deep creek channel. The traditional method of using one crane to pick up the beam from the truck and swing it around to place it was not possible. Instead, after the truck backed up to the south bank, the north beam end was picked up by a crane on the south bank. The truck then backed up farther while the north beam end was launched out over the creek by the crane. Midway across the creek, the north beam end was transferred to the crane on the north bank of the creek. Then, the crane on the south bank picked up the south beam end, and the two cranes worked in tandem to carefully move the beam out over the creek and place it on the abutments. **A**

*Michael McDonald is the director of public works for the City of Leavenworth, Kans. Lindsay Madsen is a project manager with the Kansas City, Mo., office of TranSystems.*

A box beam being readied to be lifted from the truck by the crane on the south bank of the creek after passing the north end to the crane on the north bank.



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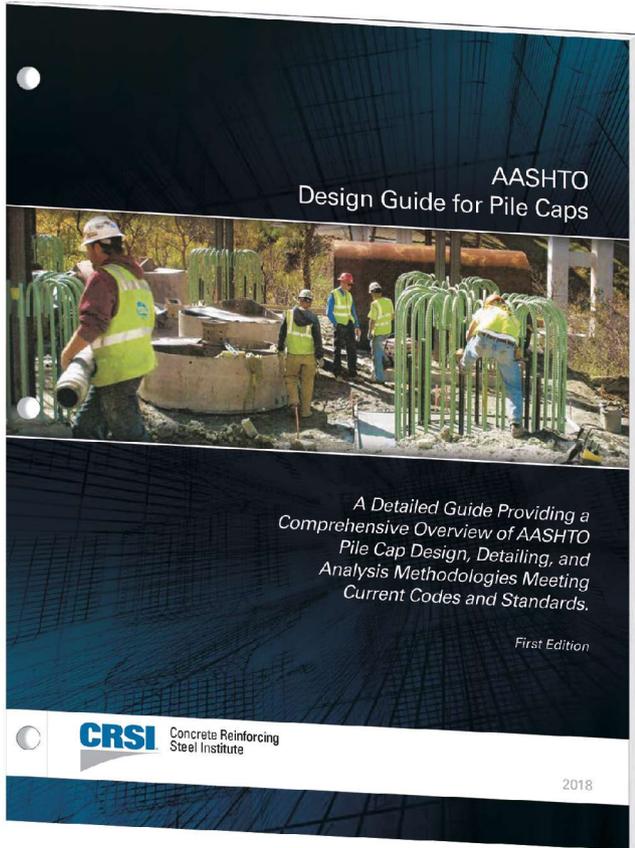
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# Design of Reinforced Concrete Pile Caps in Accordance with the 2014 AASHTO LRFD Specifications

by David A. Fanella and Gregory E. Halsted, Concrete Reinforcing Steel Institute



The Concrete Reinforcing Steel Institute's *AASHTO Design Guide for Pile Caps*. All Figures: Concrete Reinforcing Steel Institute.

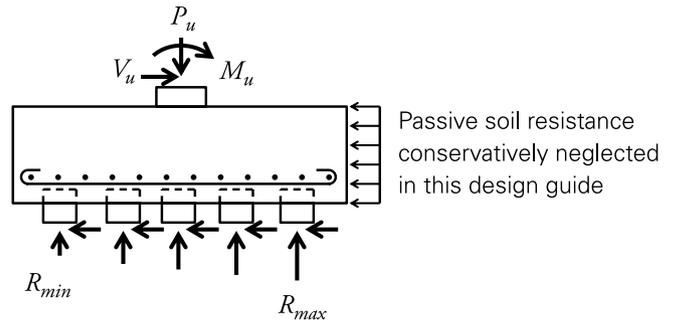
The Concrete Reinforcing Steel Institute's *AASHTO Design Guide for Pile Caps* provides comprehensive information on the analysis, design, and detailing of reinforced concrete pile caps in accordance with the 2014 edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.<sup>1</sup> The main purpose of this design guide is to provide state-of-the-art, practical procedures that engineers can apply in everyday practice without the use of finite element models.

The design guide covers both gravity and lateral load effects based on the loads defined in the AASHTO LRFD specifications. An overview of applicable load types and limit states is given in Chapter 2.

Chapter 3 shares the assumptions used to determine load distributions for two basic load cases. In Load Case I, only factored vertical loading is considered. Combined axial, shear, and moment demands are included in Load Case II.

Chapter 4 presents the pile cap configurations that are considered in the design guide. This chapter also includes a general overview of the AASHTO provisions for dimensioning and detailing pile caps and recommended reinforcement layouts.

Chapters 5 and 6 contain pile cap design procedures for vertical and lateral/overturning loads, respectively. Methods are given for flexure, one-way



Model of pile cap resisting axial force, shear force, and bending moment.

shear, and two-way shear, which can be applied to any pile configuration.

Seismic design of piles caps is covered in Chapter 7. The chapter gives an overview of seismic design provisions for pile caps supporting reinforced concrete columns for bridge structures. Although the 2014 AASHTO LRFD specifications have special provisions for foundation systems based on the seismic performance zone, similar provisions directly related to the design of pile caps are minimal.

Chapter 8 gives six practical, numerical design examples that illustrate the proper application of the required provisions. The examples were selected to demonstrate all the important information on analysis, design, and detailing covered in the design guide.

Chapter 9 includes tabulated pile cap designs for both vertical loads and combined vertical, lateral, and overturning effects. These tables can be used to quickly obtain required reinforcement and material quantities, and other information for various pile configurations with factored pile loads up to and including 600 tons.

Detailed derivations for several simplified design equations are given in Appendix A, and column-to-pile cap and pile-to-pile cap connection details are presented in Appendices B and C, respectively.

## References

1. American Association of State Highway and Transportation Officials (AASHTO). 2014. *AASHTO LRFD Bridge Design Specifications*. 7th ed, Washington, DC: AASHTO.

*David A. Fanella is the senior director of engineering at the Concrete Reinforcing Steel Institute in Schaumburg, Ill., and Gregory E. Halsted is the western region manager and transportation engineer at the Concrete Reinforcing Steel Institute in Bellingham, Wash.*

## EDITOR'S NOTE

*AASHTO Design Guide for Pile Caps* may be purchased from the Concrete Reinforcing Steel Institute by visiting <https://goo.gl/2j4xRN>.

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# Post-Tensioned Tendon Grouting on the St. Croix River Crossing

by Paul Kivisto, Minnesota Department of Transportation, and Paul Towell and Jeff Cavallin, Parsons Transportation Group

The St. Croix River Crossing connects Minnesota State Highway 36 and Wisconsin State Highway 64 over the St. Croix River just east of Minneapolis–St. Paul, Minn. Constructed by Lunda/Ames Joint Venture (LAJV) from 2014 to 2017, the bridge is a 5080-ft-long post-tensioned concrete box girder structure. The approach spans are 10- to 14-ft-deep precast concrete box-girders, and the approach gore areas and ramps consist of 10- to 18-ft-deep cast-in-place box girders. Approach spans range from 190 to 290 ft in length. The main river spans are 600-ft-long precast concrete extradosed spans composed of side-by-side, 18-ft-deep concrete box girders, which are post-tensioned using high-strength steel, multi-strand tendons inside corrugated plastic or galvanized steel ducts.

Preparing to inspect grout at grout vents.

Photo: Paul Kivisto, Minnesota Department of Transportation.



Grout being batched in a colloidal mixer. Photo: Paul Kivisto, Minnesota Department of Transportation.

Protection of a bridge's post-tensioned tendons is extremely important, and grouting, along with duct type, concrete quality, and sound joints, is a key component ensuring a bridge's durability. This article describes the grouting practices used for the post-tensioning tendons on the St. Croix River Crossing.

### Grouting Specifications

The project specifications required the use of thixotropic grouts, specific minimum and maximum temperatures for grouting, time limits on the amount of time tendons can be left ungrouted, and experienced personnel to perform the grouting.

Thixotropic grout materials are a recent advancement in grout technology. These materials are highly resistant to the formation of bleed water. They are flowable when injected under pressure into a closed duct system, but they quickly stiffen while at rest. Once at rest, thixotropic grouts are very stable

and minimize the air voids that occurred when older cement-water grouts were used. Elimination of bleed water means no excess water is left in the ducts, which can lead to early deterioration of the tendons.

Grouting operations were limited to concrete substrate and ambient air temperatures between 40°F and 100°F. Given these temperature restrictions and Minnesota's climate, grouting typically could not be performed from November through March, and grouting during the summer often had to be performed during early morning or evening hours, when temperatures were cooler. On this project, the maximum allowable time between installation of post-tensioning steel and grouting was 15 calendar days.

Precast concrete segment fabrication and erection and cast-in-place concrete operations continued during the late fall and winter months when temperatures were much colder than 40°F. Specifications



Grout being pumped into the ducts at the crossbeam in the extradosed spans (the crossbeam connects two columns of a pier). The crew is grouting the post-tensioned bars that extend across the width of the crossbeam (about a 16-ft-long bar). Photo: Paul Kivisto, Minnesota Department of Transportation.

allowed for grouting to be deferred during winter months; during that period, tendons were installed but not grouted and vapor-phase corrosion inhibitors (VPCIs) were used to minimize risk of strand corrosion. The VPCIs worked well but required a sealed duct system to provide protection through a charged atmosphere. During the project, it was noted that, in some instances, minor amounts of water got into ungrouted tendons. VPCIs do not protect tendons in such situations. Therefore, the Minnesota Department of Transportation (MnDOT) needed to be aware of cold weather segment erection practices in circumstances in which there was a risk of water intrusion prior to grouting. As a best future practice, MnDOT will consider grouting temperatures when determining whether cold weather segment erection operations will be allowed.

Standard testing was required for all grout applications to ensure that the grout as prepackaged, mixed, and as placed in the ducts met requirements for temperature, fluidity, strength, wet density, control of bleed, and chloride ion content. Standard field production test methods included modified flow cone, mud balance, and Schupack<sup>1</sup> pressure bleed testing. Field test frequencies were as follows:

- Mud balance at outlet for every tendon with five or more strands and every fourth tendon with four strands or less
- Modified flow cone for every 2 yd<sup>3</sup> of grout or every 2 hours
- Pressure bleed test and grout cube samples per each grouting operation

Project grouting operations are technically critical, and it is important

for grouting personnel to be trained and experienced. Specifications required that the post-tensioning grouting supervisor must have experience on at least four previous projects and American Segmental Bridge Institute grout technician certification. Grouting crew members were trained and under the direct supervision of personnel with at least three years of experience.

Prior to production grouting, the contractor was required to construct a grout mock-up that would be dissected to demonstrate that grouting operations could be successfully performed.

### Contractor's Operations

The bridge's precast concrete segments and cast-in-place concrete box girders are post-tensioned with tendons ranging from 19 to 31 strands in 4- to 5-in.-diameter ducts. The river pier crossbeams were post-tensioned with 52 strand tendons in 6-in.-diameter ducts. Transverse deck tendons consist of four strands in 1-in. by 3-in. rectangular plastic ducts. For grouting, LAJV used grout plants consisting of double-tank colloidal mixers, which ensured proper mixing. Some grouting was done on transverse deck tendons in the casting yard; however, most grouting was done on the erected structure. Crews typically had an approved grouting supervisor, plus two workers at the mixing plant, as well as one worker at the inlet and one at the outlet. A quality control (QC) representative for LAJV and the MnDOT/construction engineering inspection (CEI) quality assurance (QA) staff monitored the grouting operations to ensure



A cast-in-place pier table segment on an approach bridge. The round longitudinal post-tensioning ducts are 4 in. in diameter, and the flat transverse post-tensioning ducts are 1 in. by 3 in. Photo: Parsons Transportation Group.

compliance with project specifications.

A critical step prior to grouting is to check that ducts can hold air pressure. If leaks are found, the source must be identified and repaired. Leaks are most common at anchorage end caps, vent tubes, and segment joints. In this project, leaks at segment joints were repaired by drilling holes between ducts directly in the joint between segments and filling the space with epoxy. This method sealed one duct from another and avoided grout crossover. In some cases, where the tendons in adjacent ducts were already tensioned, the ducts could be grouted at the same time with use of a manifold.

### Grouting Challenges

LAJV found that thixotropic grout tended to set up quickly on warmer days, which can complicate grouting, but grouting typically proceeded very well. With more than 2000 miles of post-tensioning strand on the project, the scheduling of grouting operations was challenging. The contractor used two crews at peak times and was able to provide an adequate number of trained and experienced supervisors. At times, the 15-day maximum grouting time requirement between post-tensioning steel installation and grouting became an issue, and the project team needed to come to agreement on how to best get back within specifications.

Air leaks occurred on several occasions and were repaired as previously explained. Only one duct had grout crossover into an untensioned tendon. LAJV double-ended tensioned that tendon to the design



A modified flow cone test was required to be performed for every 2 yd<sup>3</sup> of grout or every 2 hours. Photo: Paul Kivisto, Minnesota Department of Transportation.

force. Post-grouting inspection of tendon anchorage caps and inlet/outlet vents was performed for each tendon to confirm complete and successful grout filling of the tendons, and there were only a few isolated instances of incomplete grouting or voiding. Once identified, these minor areas were repaired using either gravity-fed or vacuum grouting procedures.

Dry grout material was tracked, and any product older than six months or stored

onsite for more than one month was discarded.

### Environmental Considerations

Because the St. Croix River Crossing spans a National Scenic Waterway, the project needed to follow environmental best management practices; therefore, the grouting operations needed to be contained such that any spills, grout residue, or other hazardous materials would be contained, properly disposed of, and not enter the river or wetlands.

### QA Inspection Process

Parsons Transportation Group assisted MnDOT with QA inspections. CEI staff were required to have at least five years of experience with post-tensioned bridge construction, including grouting experience. QA inspections included verifying air-pressure testing, witnessing field production tests at the inlets and outlets, reviewing all repairs, verifying post-grouting inspection adequacy of the grouted duct, and documentation of all grouted tendons.

The project specifications for grouting the post-tensioned tendons, the grouting process by the contractor, and the QC/QA verification process implemented on the St. Croix River Crossing will lead to a durable bridge for years to come.

### Reference

1. Post-Tensioning Institute (PTI). 2012. *Specification for Grouting of Post-Tensioned Structures (PTI M55.1-12)*. Farmington Hills, MI: PTI.

*Paul Kivisto is the St. Croix River Crossing construction engineer with the Minnesota Department of Transportation in Golden Valley, Minn. Paul Towell is the St. Croix River Crossing CEI field manager and Jeff Cavallin is the St. Croix River Crossing CEI approach bridge engineer, both with Parsons Transportation Group in Minneapolis, Minn.*

### EDITOR'S NOTE

*For more details on this project, see the project article on the St. Croix River Crossing in this issue.*

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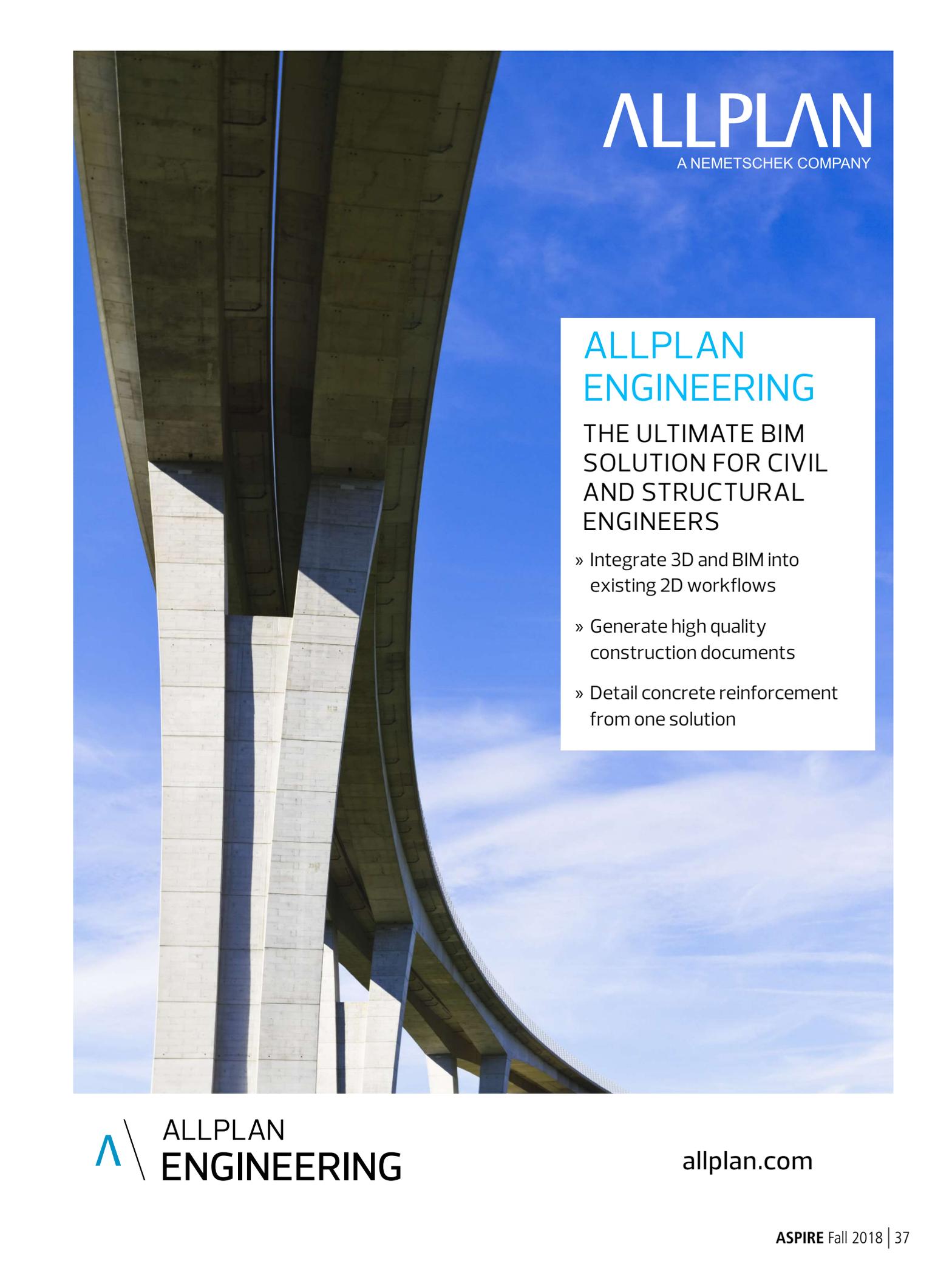
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# REDISTRIBUTION OF MOMENTS

## in Continuous Structures

by Dr. Andrea Schokker, University of Minnesota Duluth

This article focuses on the topic of moment redistribution, which should not be confused with moment distribution (that great method developed by structural engineering professor Hardy Cross for solving indeterminate structures that continues to elicit groans in structural analysis classes). Moment redistribution refers to the ability of continuous, or statically indeterminate, structures to redistribute moment at the strength limit state due to their redundancy. During the design process, analysis in the elastic range is typically performed and does not include any additional capacity of the overall structure after the elastic limit is reached. Considering moment redistribution can allow designers to account for additional capacity at the strength limit state that may be available as moment shifts (redistributes) from the section that has reached the plastic range to sections still in the elastic range.

If a continuous structure is properly detailed, it can form what is known as a “plastic hinge,” which results in a shift of moment to a different area, giving a higher overall structure capacity at the strength limit state than first assumed when looking only at the section capacity. The more degrees of indeterminacy a structure has, the greater the number of potential plastic hinges required to cause failure. This concept can be illustrated by a basic example. The following assumptions will be used for the example:

- The member has an idealized moment-curvature relationship, where a section is elastic until the design capacity (yield) is reached and then does not take any additional moment.
- After a section reaches elastic capacity, it is idealized as a hinge (resisting no additional moment).

- The section capacity is the same along the entire member, with equal capacity for positive and negative applied moment.
- When a sufficient number of plastic hinges have formed to make a member or span unstable so that a collapse mechanism is formed, the member is considered to have failed.

Consider a simply supported determinate beam as shown in Fig. 1. The maximum moment under this condition is at the midspan of the beam, and, thus, that location is where the plastic moment  $M_p$  will be reached first. If the length of the beam  $l$  is 100 ft and the section moment capacity is 1000 kip-ft, the uniform load  $w$  required to form the midspan hinge and resulting collapse is calculated as follows:

$$\frac{wl^2}{8} = 1000 \text{ kip-ft}$$

$$w = \frac{8(1000 \text{ kip-ft})}{(100 \text{ ft})^2} = 0.8 \text{ kip/ft}$$

With no redundancy in this system, a collapse mechanism is formed and the member fails. This determinate beam case does not allow any redistribution of moment.

Now, consider the case of a redundant

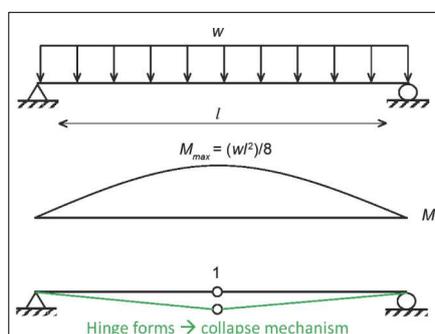


Figure 1. Simply supported determinate beam with uniform loading. All Figures: Dr. Andrea Schokker.

single-span member fixed on both ends with a uniform loading, as shown in Fig. 2a. For illustrative purposes, let's suppose we have a section capacity of 1000 kip-ft (both positive and negative moment) and a beam length of 100 ft. In this case, the plastic moment is reached first at the ends under negative moment. The moment diagram in Fig. 2b shows the moment values at the stage at which the first hinges form. The value of the applied uniform load  $w$  at this stage is calculated as follows:

$$\frac{wl^2}{12} = 1000 \text{ kip-ft}$$

$$w = \frac{12(1000 \text{ kip-ft})}{(100 \text{ ft})^2} = 1.2 \text{ kip/ft}$$

The midspan moment at this stage is only 500 kip-ft. The beam is still stable and can continue to take load at this point, but no more moment can be added where the plastic hinges have formed (Fig. 2c). Any additional moment is taken as if the beam were simply supported (Fig. 2d). If we continue to add load, we will reach a point where a hinge is developed at midspan, where the maximum positive moment is. This location was already taking 500 kip-ft of moment when the hinges at the ends were formed and, once an additional moment of 500 kip-ft is added, the midspan section reaches its moment capacity of 1000 kip-ft. The incremental load  $\Delta w$  required to form the midspan hinge and resulting collapse is calculated as follows:

$$\frac{\Delta w l^2}{8} = 500 \text{ kip-ft}$$

$$\Delta w = \frac{8(500 \text{ kip-ft})}{(100 \text{ ft})^2} = 0.4 \text{ kip/ft}$$

This gives us a total uniform load of  $w = 1.2 + 0.4 = 1.6$  kip/ft on the structure prior to reaching theoretical collapse (assuming that the hinges are formed at the elastic design capacity of the section),

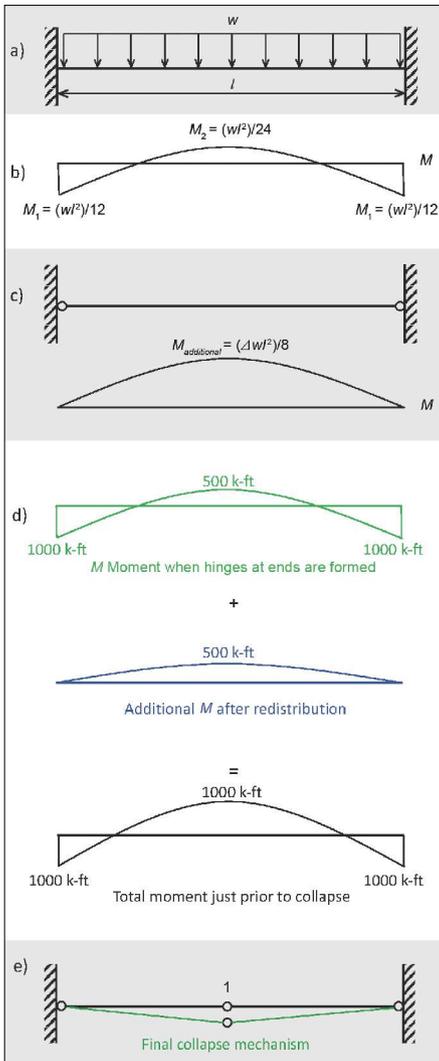


Figure 2. Redistribution of moment in a fixed-end indeterminate beam with uniform loading.

with the moment distributed as shown in Fig. 2d and the final collapse mechanism as shown in Fig. 2e. In this example, the indeterminate fixed-end beam can carry a 33% greater uniform load before theoretical collapse occurs when moment redistribution is considered.

The example gives a basic demonstration of how moments are redistributed after plastic hinges are formed. In reality, a structural concrete section will likely have different positive and negative moment capacities, based on elastic analysis.

The principles of moment redistribution are expanded in the continuous beam shown in Fig. 3a. The beam is two degrees indeterminate; therefore, it can theoretically have two hinges form prior to a third hinge that causes failure. However, the hinge location is

important. If the first hinge forms in the end spans, a collapse mechanism is formed in the span (Fig. 3b). However, if the first hinge forms in an interior span, the structure can remain stable until the third hinge forms (Fig. 3c and 3d). The locations of hinges depend on a number of factors, including section capacity at different locations, span lengths, and ductility at potential hinge areas.

The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*<sup>1</sup> cover moment redistribution in Article 5.6.3.4. The article states that, in lieu of a more refined analysis, redistribution (increase or decrease) of negative moment is allowed up to 20% of the moment as determined by elastic theory. The percentage is based on a factor (1000) multiplied by the net tensile strain in the steel  $\epsilon_t$ . Redistribution is only allowed if  $\epsilon_t$  is at least 1.5 times the tension-controlled strain limit. The article also requires that positive moments must be adjusted to account for negative moment redistribution.

Given the complexity of continuous concrete structures (particularly when including secondary moment effects, as discussed in the Summer 2018 issue of *ASPIRE*<sup>®</sup>), it is important for the designer

to fully understand the implications of the redistribution of moments, as well as when they may not redistribute because of the formation of a collapse mechanism. Additionally, the section where a plastic hinge may form must be provided with sufficient ductility; therefore, particular care must be given to the detailing of reinforcement.

Ken Bondy<sup>2</sup> authored a helpful technical paper that goes through multiple examples with post-tensioned continuous members and builds on the basic theory of plastic hinge analysis discussed in this article. Designers are likely to find his examples instructive as they think through the moment redistribution process to create a practical concrete design.

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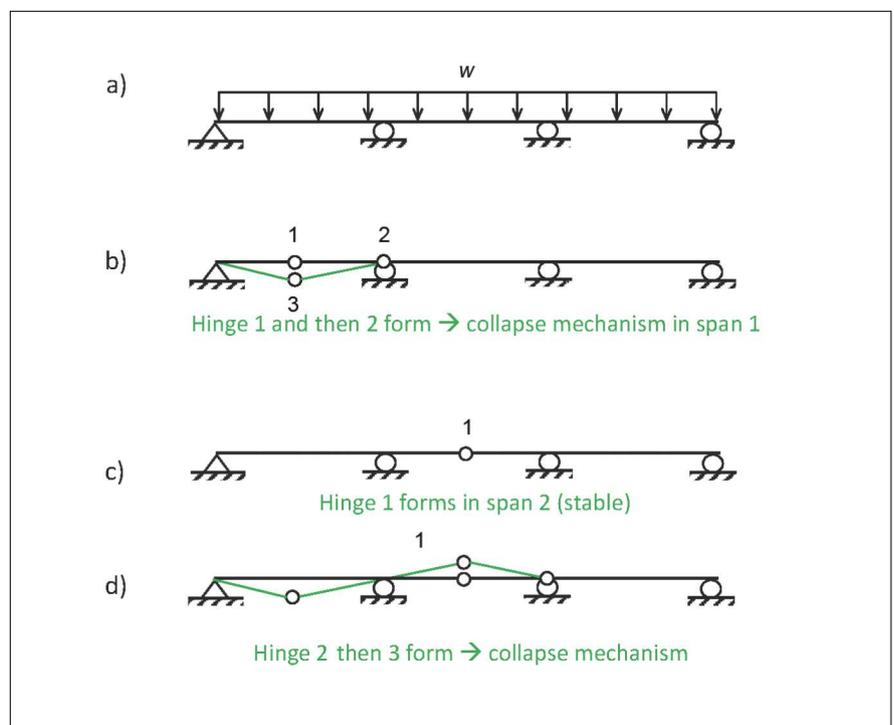


Figure 3. Possible locations of plastic hinges in a multi-span continuous beam.

# Addressing Concrete Issues for Drilled-Shaft Foundations



by Silas C. Nichols, Federal Highway Administration

The Federal Highway Administration's (FHWA's) National Geotechnical Team has been working with industry partners to better understand factors contributing to the performance of concrete when used in underground mass placements such as drilled shafts. Innovations in drilled-shaft construction equipment over the last two decades, combined with increased load-carrying demands for foundation elements, have resulted in significantly larger and deeper shaft excavations that have tested the ability of conventional concrete mixtures to meet necessary performance requirements.

The construction conditions for drilled-shaft foundation projects are more complex than those for other reinforced concrete structures. Therefore, the concrete mixtures used for shaft excavations must be designed to address specific application requirements.

The most important requirements are those

that contribute to the workability of fresh concrete during transport and placement operations. Concrete may be transported long distances to remote sites and pumped long distances. It may be required to flow readily through a tremie and through congested reinforcement under slurry. Additionally, concrete may have to remain workable for 4 to 8 hours, or longer, in wide-ranging ambient temperature conditions.

Fresh concrete placed in drilled-shaft operations must also consolidate under its own weight without the assistance of vibration, and it must remain stable without segregation, excessive bleeding, or excessive heat of hydration. These requirements for workability are now relatively common in drilled-shaft construction, and balancing them has become a significant challenge to engineers.

To address some of these issues, FHWA is currently leading a research effort to study factors that contribute to the performance of concrete

placed for geotechnical applications, and specifically drilled-shaft foundations. The primary objective of the research is to develop performance standards that correlate to basic demands for drilled shafts and allow for better concrete mixture designs.

## FHWA Guidance for Drilled-Shaft Concrete

The basic demands for concrete in drilled-shaft applications are currently summarized in FHWA's *Geotechnical Engineering Circular No. 10* as follows:<sup>1</sup>

- **Workability:** The concrete must have the ability to flow readily and fill the shaft excavation completely. The concrete must readily pass through the reinforcement without blocking to achieve thorough contact with the surrounding soil or rock. The concrete must be self-leveling within the excavation and consolidate under self weight; vibration of concrete in a borehole is not possible or practical.
- **Workability retention:** With underwater tremie placement, or when the casing must be withdrawn after completion of concrete placement, the drilled-shaft concrete must retain workability and have controlled setting times suitable for completion of placement operations.
- **Stability:** While providing the high degree of workability required, the fresh concrete must still have robust stability and resist any tendency to segregate or bleed. The paste within the concrete should have a high degree of cohesion so that coarse aggregate particles are evenly distributed, and water within the mixture should remain distributed without a tendency to bleed and result in nonuniform properties or bleed-water channels.
- **Durability:** The concrete cover on the reinforcement must provide low permeability so as to minimize the potential for corrosion of the reinforcement. If the subsurface environment is aggressive or may become aggressive during the life of the foundation, the concrete should be designed to have high density and



Tremie being used for concrete placement for a drilled shaft. All Photos: Federal Highway Administration.

low permeability so that the concrete is able to resist the negative effects of the environment.

- *Appropriate strength and stiffness:* The concrete must provide the strength and stiffness necessary to meet structural performance requirements.

In most cases, drilled shafts are not subject to large structural stresses, so strength demands are relatively ordinary compared with the extreme workability requirements cited above.

### Research Priorities

Ongoing FHWA-led research is focusing on several uncertainties related to workability, durability, and thermal issues related to concrete used for deep foundations. The current research areas prioritized for investigation are:

- *Evaluate or develop practical tests to assess and rate the potential for concrete mixtures to segregate or bleed excessively.* Researchers are attempting to clarify how much bleed is acceptable. This effort is being leveraged by ongoing research by the European Federation of Foundation Contractors and the Deep Foundations Institute.
- *Address concerns about thermal issues in large-diameter drilled shafts.* Investigators are working to quantify risks for drilled-shaft concrete damage resulting from high temperatures, especially because there are no documented cases of such damage. The research effort

seeks to establish clear threshold temperatures and temperature differentials beyond which damage can be expected.

FHWA believes that a better understanding of these issues may reduce some of the most critical uncertainties and provide the basis for the development of industry guidelines regarding concrete for use in deep foundations.

### Concluding Remarks

The FHWA research is focused on drilled shafts because they are one of the primary below-ground concrete applications considered by transportation agencies. However, the findings of this study will also be applicable to other below-ground structural elements, including secant and tangent pile walls, slurry (concrete diaphragm) walls, tremie seals (pedestal foundations), building mat foundations, and cast-in-place tunnel and shaft structures.

The research is being performed in three phases. The first phase, which was completed in 2016, included a comprehensive literature review, a survey of transportation agencies, and the identification of topics that should be prioritized for additional research. The second phase is ongoing and is focused on modeling and testing for thermal issues in concrete. The third phase will begin in fall 2018 and will be focused on field and laboratory testing to better understand



Concrete placed by free falling from a chute for a drilled shaft, which is a common practice in dry shaft excavations. Field studies have shown that concrete mixtures designed for dry placement in drilled shafts can be dropped freely for distances up to about 80 ft without issues related to segregation.

bleed and segregation. The expectation is that the efforts will be completed by late 2019.

For additional information, please contact Silas Nichols, Principal Bridge Engineer—Geotechnical, Federal Highway Administration Office of Bridge Technology; silas.nichols@dot.gov.

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# Confinement Reinforcement Requirements for Concrete Piles

by Stephen J. Seguirant, Concrete Technology Corporation

The origins of confinement reinforcement requirements—specifically, circular spiral for square, octagonal, or circular concrete piles—have long been somewhat of a mystery. The outcome has been a myriad of prescriptive rules, which vary widely depending on the code, standard, or specification applicable to a project. The graph below shows the historical variability of some of these prescriptive requirements for 24-in.-octagonal prestressed concrete piles. Inexplicably, the requirements also vary significantly depending on whether the piles are cast-in-place or precast concrete and driven. These provisions affect the size, spacing, and depth below the pile head where varying quantities of spiral reinforcement are required. Clearly, these provisions significantly affect the cost of piles. This article reviews the status of recent research and its applicability to concrete piles.

## Background

The primary purposes of spiral reinforcement are to provide confinement to the pile concrete core so that it behaves in a ductile manner under combinations of axial and lateral loads, to provide support to restrain buckling of nonprestressed longitudinal reinforcement, and to provide adequate shear strength. The lateral loads imposed by earthquakes are of great concern. Therefore, the spiral reinforcement requirements naturally escalate as the Seismic Design Category (SDC) increases.

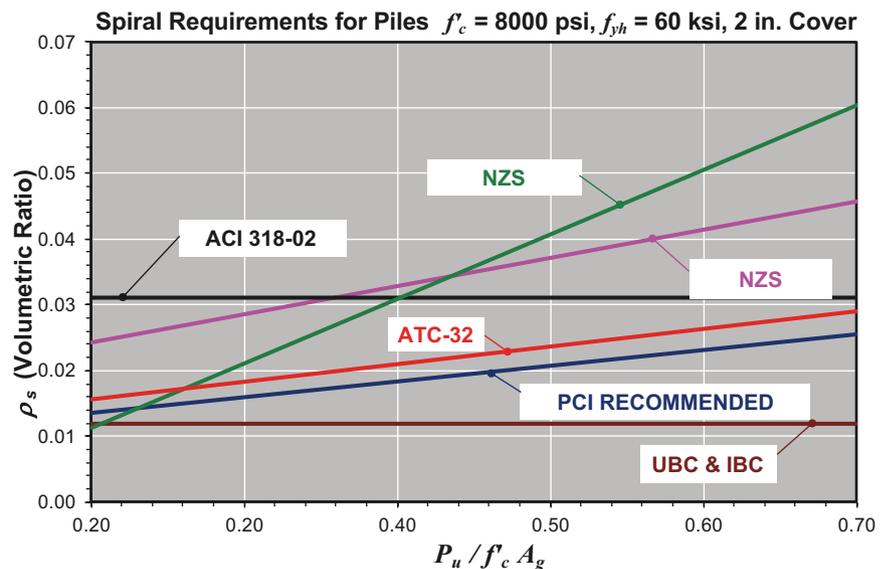
Spiral reinforcement in high SDCs, sized in accordance with current requirements, can become very heavy, and, in some cases, may be unconstructable, particularly for smaller pile sizes. For driven piles, the spiral also confines the concrete at the head and tip to mitigate bursting during driving. Mild steel driving rings have also been used for this purpose.

In 1993, the Precast/Prestressed Concrete Institute (PCI) published its "Recommended Practice for Design, Manufacture, and Installation of Prestressed Concrete Piling" (RP).<sup>1</sup> This document provided equations for determining spiral volumetric ratios in moderate and high seismic regions, based primarily on research performed in New Zealand by Joen and Park.<sup>2</sup> However, the equation in the PCI RP for high seismic regions provided roughly half of the spiral volumetric ratio recommended by the New Zealand research shown in the graph. This PCI equation was proposed in the apparent belief that half of the target ductility sought by the New Zealand researchers would be sufficient for high seismic regions in the United States, although the reason for this conclusion is not clear. The PCI RP equation was adopted in the 2000 edition of the International Building Code (IBC); however, IBC 2000 maintained the upper limits on volumetric ratio from previous

editions.<sup>3</sup> Chapter 20 of the *PCI Bridge Design Manual*<sup>4</sup> recommends the full volumetric ratio of spiral resulting from the New Zealand research, although this recommendation has not been adopted into American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.<sup>5</sup>

## Iowa State University Research

In light of the uncertainty surrounding prescriptive requirements for spiral reinforcement, PCI funded a research project in 2006 at Iowa State University to develop a rational means of determining spiral volumetric ratios in prestressed concrete piles. The results of this research were detailed in a final report,<sup>6</sup> and a summary was published in the *PCI Journal*.<sup>7</sup> A single equation is proposed to quantify spiral volumetric ratios depending on target curvature ductility. A value of target curvature ductility is suggested for high seismic regions based on a review of literature published on pile testing and a



Variability of spiral reinforcement requirements based on axial load level for 24-in.-octagonal prestressed concrete piles. Note: ATC = Applied Technology Council; NZS = New Zealand Standard. All Figures and Photos: Concrete Technology Corporation.



Driving 24-in.-octagonal prestressed concrete piles at Pier 4, Port of Tacoma, Wash.

“back-end” analysis of piles subjected to actual earthquakes. Lower values of target curvature ductility are also suggested for low and moderate seismic regions. Values of target curvature ductility other than those suggested, such as those derived from a performance-based analysis, can also be used.

The research establishes axial load limits for different sizes and shapes of prestressed concrete piles. The purpose of these limits is to ensure that, under combined axial load and moment, the pile cracks before the concrete cover spalls. When the opposite is true, the decrease in moment capacity due to concrete cover spalling is significant, and the pile does not behave as intended.

The 2018 edition of the IBC adopted these recommendations in place of the previous PCI RP provisions, while maintaining the same upper limits on volumetric ratio provided in previous editions.<sup>8</sup>

The American Concrete Institute (ACI) Committee 318 intends to adopt requirements for deep foundations in the 2019 edition of *Building Code Requirements for Structural Concrete (ACI 318-19)*. Historically, ACI 318 has not included provisions for piles, unless portions of the pile are not adequately laterally restrained by stiff soil, and for SDCs D, E, and F. Even then, with the exception of provisions related to seismic detailing, no specific provisions existed for piles, which were essentially to be designed under the same rules as columns. Provisions in the AASHTO

LRFD specifications for confinement reinforcement in piles are similar to the ACI 318 provisions for columns. ACI Committee 318 is currently balloting provisions for piles similar to those in the 2018 IBC. AASHTO Subcommittee T-10 on Concrete Design should also consider revisions to the AASHTO LRFD specifications to incorporate the most recent research on concrete pile confinement reinforcement.

## Precast, Prestressed Concrete Piles versus Cast-in-Place Piles

As mentioned in the opening paragraph of the article, spiral reinforcement requirements vary significantly depending on the type of concrete pile selected. Most of these differences are inexplicable given that different types of concrete piles should be expected to perform similarly under the same conditions. Also, differences that should be considered between the pile types, such as susceptibility to downdrag, cross-sectional tolerances, and tolerances for placement of reinforcement, are generally not considered in prescriptive design provisions for buildings. Such differences should result in higher resistance factors for precast concrete piles than for cast-in-place piles, as is the case for bridge construction. Mays provides an excellent discussion of these aspects of concrete pile design and detailing.<sup>9</sup>

Because time is of the essence for the 2019 release of ACI 318, it is not possible for these differences to be remedied for ACI 318-19. As a member of ACI Committee 318, the author has requested that these discrepancies be taken up as new business in the next code cycle.

Unloading of 24-in.-octagonal prestressed concrete piles on barge at Pier 4, Port of Tacoma, Wash.



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# The Next Segment for the American Segmental Bridge Institute

As William R. “Randy” Cox ends his term as executive director of the American Segmental Bridge Institute, he reflects on the organization’s accomplishments and future.

by Craig A. Shutt



During ASBI’s 2017 convention in New York, N.Y., Cox and other attendees toured the construction of the new segmental box girder approaches for the Bayonne Bridge, which spans the Kill Van Kull connecting Bayonne, N.J., with Staten Island, N.Y. All Photos: American Segmental Bridge Institute.

The American Segmental Bridge Institute (ASBI) will have a new leader this fall, as William R. “Randy” Cox hands the executive director reins to Gregg A. Freeby, P.E. Freeby previously worked for 31 years with the Bridge Division of the Texas Department of Transportation (TxDOT) and was appointed division director and state bridge engineer in October 2011. Freeby left TxDOT at the end of August 2018 and begins with ASBI in October, providing a transition period before Cox leaves on December 31.

## Cox’s Time at ASBI

Like Freeby, Cox worked for TxDOT before becoming executive director of ASBI. While with TxDOT, Cox led a team doing structural inspections in 1983 for the Bear Creek Bridge, which became the prototype for the San Antonio, Tex., “Y” segmental bridge project. He also provided construction-engineering support for several segmental and cable-stay projects and participated in a concrete segmental bridge durability-scanning tour of Europe sponsored by the Federal Highway Administration.

His ASBI tenure began on November 1, 2008, when he succeeded Cliff Freyermuth. Cox established a new office in Buda, Tex., just north of Austin, from which Freeby will continue to lead ASBI.

“The job [of executive director] piqued my interest, and I knew the window to take the position would probably not open again for some time,” Cox says. “I’ve always had a strong interest in segmental bridges, both design and construction. Post-tensioned concrete was one of my favorite areas, and I saw this [position] to be a great opportunity to advance that.”

TxDOT was the first owner-member of ASBI, and Cox had served as one of its representatives to the institute. Becoming the executive director of ASBI brought him back to those roots. “I was able to rekindle old friendships with a strong idea of the work the group did.”

Cox took over at ASBI just as the Great Recession hit, but the association—and the industry—weathered the storm. “There definitely was a drop in the number of bridges being built, but our membership grew, and we maintained our convention attendance in that period,” he reports. The organization’s strength

## The National Concrete Bridge Council

As he leaves ASBI, Cox also leaves his post as chair of the National Concrete Bridge Council (NCBC), with William Nickas of the Precast/Prestressed Concrete Institute (PCI), and Editor-in-Chief of *ASPIRE*®, taking over.

Nine organizations, including the American Segmental Bridge Institute (ASBI), belong to NCBC. Their collective goal is to promote quality in concrete bridge construction through their own specialized focuses.

NCBC “is a great organization that allows members to discuss new techniques and issues and get everyone on the same page,” Cox explains. “We can share different perspectives to examine all impacts of ideas and contribute suggestions.” They also meet with Federal Highway Administration representatives to help resolve issues that arise.

“We look for ways to collaborate to ensure the best solutions and highest quality approaches,” Cox says. “I have no doubt that William will continue to move the group and the industry forward and keep NCBC programs moving smoothly.” For more information about NCBC, visit [nationalconcretebridge.org](http://nationalconcretebridge.org).

at this time “showed that the industry understood the value of networking and trading ideas.”

Cox is particularly proud that membership by corporations grew significantly during his tenure, from 50 companies in 2009 to 82 today. Corporate members “see the value that we can provide to them and find membership to be a strong investment.”



ASBI regularly offers a variety of training programs, such as this grouting verification class in 2014 in Austin. As part of its development of an update on grouting–certification training in 2016, ASBI created seven videos at the Florida Department of Transportation lab. The videos are available on ASBI's website and YouTube.

He also points to the number of owner-members today. When he arrived, only three state departments of transportation were members; today, 13 belong to ASBI. "We can gain the client's perspective and target our programs to serving each part of the industry better with their input."

For the organization's 25th anniversary in 2013, Cox and his team developed a strategic plan to guide growth and development for the next 25 years. ASBI reorganized its activities under five committees:

- Information Management, which collects, organizes, analyzes, and presents information relevant to segmental bridges
- Education, which encourages the use of technical knowledge and explains the

value of segmental bridges to increase their application

- Technology and Innovation, which is especially focused on sustainability, durability, environmental and public impacts, and asset management
- Communications, which is aimed at increasing awareness of ASBI and segmental bridges
- Membership, which seeks to broaden the base and partner with organizations that complement ASBI's goals, such as the National Concrete Bridge Council, which Cox also chaired until July of this year (see the sidebar)

These committees are prepared to collaborate with each other and other organizations to address key issues. For example, when concerns were raised

about chlorides appearing in grout in 2010 and soft-grout issues arose in 2012, ASBI "worked closely with the Post-Tensioning Institute [PTI] and others to develop new grouting specifications and incorporate new training techniques, and our new structure will help us respond to those issues," Cox notes. That work resulted in a comprehensive new specification for grouted post-tensioning installations that ASBI and PTI are working to make a uniform standard across states. "The lessons one state learns often can transfer, and we want to be part of the dissemination of those techniques," Cox says. Several iterations of the specification have been produced, each building on past experience.

Cox points to ASBI's outreach to students as another notable achievement during his time as executive director. "I'm proud to have begun the tradition of bringing students to our convention and introducing them to what segmental-bridge design is about," he says. "Not all will be intrigued, but some will be and want to learn more. I'm hoping we inspire some students to become the next generation of bridge engineers."

## Looking Forward

Cox has no specific plans for what he will do once he finishes the transition, but he is looking forward to new opportunities. "I want to begin the next chapter," he says. He expects his agenda will fill with activities involving his three granddaughters, and his field trips will involve museums rather than bridge sites.

"The hardest part of the decision [to step down as executive director] was knowing I would no longer see my industry colleagues and friends," Cox notes. "I enjoy discussing our challenges and catching up on new ideas and their lives. But there has to be a time to move on." Cox leaves ASBI feeling optimistic. He believes Freeby's tenure will bring innovative ideas to ASBI and help the organization continue making progress. "A fresh perspective will bring new energy, and I have no doubt that Gregg can take ASBI to the next level." Moreover, "I have every confidence that Gregg will continue to strengthen ASBI and work to educate, encourage, and inspire owners, designers, and contractors to innovate with concrete segmental bridges." 



Students attending the 2014 ASBI convention were able to tour the Pearl Harbor Memorial Bridge (Q Bridge) in New Haven, Conn. The bridge was the first concrete segmental extradosed structure in the United States.

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# Upcoming Changes to the AASHTO LRFD Bridge Design Specifications

by Dr. Oguzhan Bayrak, University of Texas at Austin



Photo: Vermont Department of Transportation.

This article covers the four working agenda items prepared by American Association of State Highway and Transportation Officials (AASHTO) Technical Committee T-10 that were approved at the 2018 meeting of the AASHTO Committee on Bridges and Structures, as well as the related changes to be made to Section 5 of the *AASHTO LRFD Bridge Design Specifications*.

## Effect of Post-Tensioning Ducts on Shear Strength

Given the growing popularity of spliced girders and the use of both plastic and steel ducts, the Texas Department of Transportation sponsored research to evaluate the shear strength of full-scale specimens and make recommendations.<sup>1</sup> Researchers conducted 11 shear tests (10 with ducts and one without) to failure, using a total of seven full-scale bulb-tee specimens. The targeted variables in the testing included (a) presence of grouted post-tensioning ducts, (b) post-tensioning duct material (plastic or steel), (c) duct-diameter-to-web-width ratio, and (d) transverse reinforcement ratio. In the tests, grouted plastic ducts did not significantly reduce girder shear strength when compared with grouted steel ducts. The researchers statistically evaluated the results of these and 34 other similar tests to develop and refine strength reduction factors to account for the presence of ducts. The newly adopted design provisions more accurately represent the observed crushing behavior of compression struts and the resultant limitation on the contribution of transverse reinforcement in the truss shear-resistance mechanism.<sup>1</sup>

## Development Length of Welded Wire Reinforcement

This change aims to eliminate a potential misinterpretation of Article 5.10.8.2.5b introduced prior to the 7th edition and to clarify existing specifications regarding splice and

development lengths for welded wire reinforcement. A new equation identifies the modification factors applicable to welded wire reinforcement. Also, the commentary has new figures to help designers interpret the provisions. Depending on how designers previously interpreted the provisions, there may be minor changes to the development and splice lengths for welded wire reinforcement. The approved provisions also provide better consistency with the provisions of ACI 318-14.<sup>2</sup>

## Stability of Precast, Prestressed Concrete Girders

With optimized sections, and through use of high-performance/high-strength materials, spans of pretensioned girders have been increasing in recent decades. Record-breaking spans, with lengths exceeding 200 ft, have been constructed in Washington, Nebraska, and Florida. The stability of pretensioned concrete girders may govern the design of long-span girders. Commentary and references are therefore added to Section 5 to emphasize the safety implications of stability considerations.<sup>3,4</sup>

## Cover Requirements for Different Types of Reinforcement

Corrosion-resistant steel, such as AASHTO M 334 bars, are increasingly used in bridge structures due to their durability and strength. This change in the specifications allows designers to appropriately use reduced concrete cover for corrosion-resistant, epoxy-coated, and galvanized reinforcing steel while providing an equivalent or longer service life than that of ordinary uncoated reinforcing bars. Experiments and published analytical results demonstrate the viability of using reduced clear cover for ASTM A615 and A706 reinforcement while complying with AASHTO crack width requirements.<sup>5-7</sup>

The changes discussed in this article offer significant improvements to the specifications and will appear in the 9th edition of the AASHTO LRFD specifications. Upcoming articles will present the technical background and implications of some of these changes for the industry.

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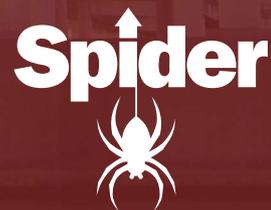
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