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THE CONCRETE BRIDGE MAGAZINE
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Kelly McNutt Consulting: Experts in Constructability

Start-up firm draws on decades of experience to crunch the numbers behind the scenes

AUTOMATED PEOPLE MOVER AT LAX
Los Angeles, California

HARKERS ISLAND BRIDGE
Carteret County, North Carolina


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EDITORIAL

Photo: PCI.

Which New Technology Will Be the Next Game Changer for Concrete Bridges?

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

During the course of our days, we are exposed to a myriad of thoughts, concepts, and ideas. New products and processes seem to hit the marketplace daily.

When I was a kid, my brother and I would rush to the driveway on Sunday mornings, trying to beat each other to the Sunday paper. We were after the "in-full-color" comics section, where Dick Tracy, everyone's favorite rugged police detective, was on a case. I loved that he had a super-cool two-way wrist radio (circa 1946), which was upgraded to a two-way wrist TV in 1964. It's funny how life imitates art: Apple released the Apple Watch—a variation on the two-way wrist radio—in 2014. By the way, I don't find the Sunday paper on my driveway anymore; it's been digitized.

I recently read an article on e-fuels. While synthetic fuels have been around for decades, e-fuels, which are developed or created using a recycling process, are a relatively new fuel source. The process is scientifically based, with a heavy emphasis on chemistry, and uses carbon dioxide and hydrogen to make methanol, which is then converted to gasoline. E-fuel production levels are currently relatively low, and the energy required for production is immense, but the concept is intriguing and gaining momentum. Is a sustainable fuel source for the internal combustion engine very far off?

It seems like every time I watch the nightly news, there's another story on artificial intelligence (AI). Even the name makes me a bit uneasy. Artificial refers to something created or produced by humans rather than occurring naturally, and a Google search provides this definition of intelligence: "the ability to acquire and apply knowledge and skills."

Engineers are all about applying knowledge and skills, and we create "stuff" that doesn't occur naturally in nature. Yikes! Are *we* AI-ers? I don't believe we are, but it does make you wonder.

So, how does AI impact our business? Does it influence firms' decisions about hiring, or what equipment contractors use to build a bridge? How does AI affect engineering training programs and college coursework? There are more questions than answers, but my gut tells me we need to get smart on this quickly, as we're already behind. The AI train has left the station and is heading for concrete designers, producers, design/construction firms, and departments of transportation near you. We can benefit from AI, but we must not become complacent.

In the Winter 2016 issue of *ASPIRE*®, I penned the editorial "Make a New Year's Resolution: 'Stay in Touch with Suppliers'." Today seems like the right time to revive that resolution, as there are critical questions we need to ask ourselves and our suppliers. What is the next new thing, process, or product for our bridge construction community? Who drives it? Who delivers it to the market? What new applications or construction methods improve our industry?

Three-dimensional (3-D) scanning is a powerful tool already being used to create as-built models (that's right, models, not drawings). In just minutes, it can be used to gather data to fully describe and model an intricate railing, bearing, or other element. Additive manufacturing (3-D printing) can then be used to fabricate a replacement or the form for the element based on the model. Can additive manufacturing be used to produce complex reinforcement, whatever the material?

Some have suggested that the concrete bridge community will undergo a renaissance as we deploy new technologies—such as new types of prestressing strands, new types of coating or materials for reinforcing bars, new post-tensioning (PT) hardware, or even ultra-high-performance concrete—combined with additive manufacturing techniques like 3-D printing and scanning. To make this renaissance a success, we all need to get back in touch with our vendors (suppliers of software, equipment, coated reinforcement, PT, and raw materials) and investigate potentially cost-effective ways to use AI, 3-D printing and scanning, and more to improve the ways we design, manufacture, deliver, construct, and inspect resilient, long-lasting concrete bridges in the United States. A

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

Managing Technical Editor
Dr. Krista M. Brown

Managing Technical Editor Emeritus
Dr. Reid W. Castrodale

Technical Editors
Monica Schultes, Angela Tremblay

Program Manager
Trina Brown • tbrown@pci.org

Associate Editor
Thomas L. Klemens • tklemens@pci.org

Copy Editors
Elizabeth Nishiura, Laura Vidale

Layout Design
Walter Furie

Cover
The sweeping alignment of the Los Angeles International Airport's new automated people mover provides travelers with a one-of-a-kind view of the iconic Theme Building. Photo: HDR Inc.

Ad Sales
Scott Cunningham • scunningham7@aol.com
(678) 576-1487 (mobile) or
(770) 913-0115 (office)

Reprints
lisa scacco • lscacco@pci.org

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Rebar Splicing Mechanical Couplers
Concrete Crack Control

CONTRIBUTING AUTHORS

Raj Ailaney is a senior bridge preservation engineer with the Federal Highway Administration (FHWA) Office of Bridges and Structures in Washington, D.C. He also chairs the FHWA Bridge Preservation Expert Task Group.

Dr. Oguzhan Bayrak is a chaired professor at the University of Texas at Austin, where he serves as the director of the Concrete Bridge Engineering Institute.

John Cross is a consultant for and former vice president of the American Institute of Steel Construction.

Roy L. Eriksson is president of Eriksson Technologies Inc., which specializes in precast concrete design, and Eriksson Software Inc., a software development firm.

Emily Lorenz is an engineer and independent consultant who specializes in life-cycle assessment, green structures and practices, and energy efficiency, as well as building codes and standards work.

Dr. Gregory Lucier is an associate research professor and manager in the Department of Civil, Construction, and Environmental Engineering and manager of the Constructed Facilities Laboratory at North Carolina State University.

Dr. Rudi Seracino is a professor of structural engineering and the associate head for undergraduate programs in the Department of Civil, Construction, and Environmental Engineering at North Carolina State University.

CONCRETE CALENDAR 2023–2024

The events, dates, and locations listed were accurate at the time of publication. Please check the website of the sponsoring organization.

October 1–4, 2023
AREMA Annual Conference with Railway Interchange
Indiana Convention Center
Indianapolis, Ind.

October 3–6, 2023
PTI Committee Days
Ritz-Carlton Cancun
Cancun, Mexico

October 4–8, 2023
PCI Committee Days Conference
JW Marriott Tampa
Tampa, Fla.

October 14–16, 2023
PTI Certification Week
Terracon Consultants
Nashville, Tenn.

October 29–November 2, 2023
ACI Concrete Convention
Boston Convention Center
and Westin Boston Waterfront
Boston, Mass.

November 5–8, 2023
ASBI Annual Convention and Committee Meetings
Westin La Paloma Resort and Spa
Tucson, Ariz.

November 12–18, 2023
PTI Certification Week
Commons Conference Center
Austin, Tex.

January 7–11, 2024
Transportation Research Board Annual Meeting
Walter E. Washington
Convention Center
Washington, D.C.

January 22–25, 2024
World of Concrete
Las Vegas Convention Center
Las Vegas, Nev.

February 6–9, 2024
PCI Convention at The Precast Show
Hyatt Regency
Denver, Colo.

March 24–28, 2024
ACI Concrete Convention
Hyatt Regency New Orleans
New Orleans, La.

April 4–17, 2024
PTI Convention
Westin Indianapolis
Indianapolis, Ind.

June 3–5, 2024
International Bridge Conference
Marriott Rivercenter
San Antonio, Tex.

June 16–21, 2024
2024 AASHTO Committee on Bridges and Structures Meeting
Westin Indianapolis
Indianapolis, Ind.

September 15–18, 2024
AREMA 2024 Annual Conference and Expo
Kentucky International
Convention Center
Louisville, Ky.

September 23–27, 2024
PCI Committee Days Conference
Renaissance Nashville
Nashville, Tenn.

October 1–4, 2024
PTI Committee Days
Ritz-Carlton Cancun
Cancun, Mexico

October 20–23, 2024
ASBI Annual Convention and Committee Meetings
Loews Atlanta Hotel
Atlanta, Ga.

Editor's Note

In November 2022, 58 attendees representing post-tensioning (PT) bridge constructors, inspectors, subject matter experts, and bridge owners gathered in Austin, Tex., for a PT technology exchange. They met to discuss the progress and current state of practice in PT technology and associated materials. Following the presentations and owner roundtable discussion, the *Post-Tensioning Technology Exchange: Outcomes Report* was assembled to summarize and share the body of knowledge from the expert contributors. Both the event and the publication are the result of a collaboration between the Federal Highway Administration and the American Segmental Bridge Institute, bringing together PT technology experts with extensive knowledge in bridge design, inspection, management, and research, as well as in PT materials and installation. The *Post-Tensioning Technology Exchange: Outcomes Report* is now available at the following link: https://international.fhwa.dot.gov/programs/mrp/docs/FHWA-PL-23-009.pdf.

Kelly McNutt Consulting: Experts in Constructability

Start-up firm Kelly McNutt Consulting draws on decades of experience to crunch the numbers behind the scenes

by Monica Schultes

Relative newcomer Kelly McNutt Consulting LLC (KMC) has quickly established itself as an invaluable resource for designers and public agencies. The firm draws on its employees' decades of construction, planning, and engineering expertise to provide constructability input and construction estimates for complex bridges.

Complex Bridges

Given the increased need to repair and replace aging infrastructure, complex bridge projects are a high priority for transportation agencies. However, these challenging projects can go off the rails with regard to budget or schedule—or both—if not properly planned.

According to a study by consulting and investment banking firm FMI,[1] bridge and tunnel megaprojects (that is, projects with budgets over $1 billion) on average incur 35% cost overruns. To improve project outcomes on complex bridge projects that can take years to finish, it is critical to perform a complete engineering and risk analysis before breaking ground.

Kelly McNutt, principal and founder of KMC, believes that "if project owners spend a small percentage on early-stage engineering, they will achieve better results in on-time and on-budget delivery." These early evaluations allow the team to consider issues that can be resolved or avoided before construction starts, saving time and money.

McNutt has assembled a team of construction professionals who have been involved in numerous cable-stayed and concrete segmental bridge projects in North America. They use their industry experience and expertise to provide valuable support to such complex projects during the development stages. Since its founding in January 2020, KMC has been invited to consult on some of the most iconic bridge projects in the United States.

Win-Win Strategy

McNutt started her firm with a focus on win-win strategies, guided by her deep-seated belief that if KMC could engage with the owner during the design process, the result would be better outcomes for all parties, including the traveling public. KMC approaches each project with a focus on not just what is being built, but how it is being built, and what is needed to build it within the allotted budget and schedule.

KMC can be most helpful to owners when the consultants are engaged early in the planning stages of a project. "That is when construction budgets are developed and schedules are publicized, and it sets the foundation for the scope of work that will be funded, contracted, permitted, and introduced to social-justice stakeholders," explains McNutt. In the later stages of project development, the opportunity for substantial improvement has typically already come and gone. "You really have to get involved early to have a positive influence. If not, that ship has sailed," says Ralph Salamie, senior manager and director at KMC.

> "You really have to get involved early to have a positive influence. If not, that ship has sailed."

Many owners seek alternative delivery methods to enable them to bring a contractor on board during design development. When conventional

A rendering of the Gordie Howe International Bridge between Detroit, Mich., and Windsor, Ontario. Kelly McNutt Consulting provided Parsons Transportation Group, the owner's engineer, with independent estimates, construction scheduling, and construction management support. Figure: Windsor-Detroit Bridge Authority.

design-bid-build procurement restricts early input from a contractor, agencies and designers have turned to KMC to provide the perspective of those who have worked on the construction side of projects. “That is one of the reasons why our business has been successful—it allows for input early on from someone other than a contractor,” explains Salamie.

Bottom-Up Estimates

Traditionally, agencies have relied on their database of bid tabulations and unit prices from past projects to estimate budgets. Since the start of the COVID-19 pandemic, the inaccuracies of this estimating method have been exacerbated by unprecedented material price escalations and labor shortages. “I heard from several owners and designers that they need bottom-up contractor-style estimates to establish budgets that are in line with real-world bids.” says Salamie. In other words, “Estimate like a contractor.”

All KMC employees were previously employed by contractors and have experience in building and estimating projects. “Estimating like a contractor is what we know,” says McNutt. “We begin with a work plan and develop the staging and construction means and methods as we would if we were building the job,” adds Salamie. When clients ask about the extra cost to create a construction schedule, Salamie says he responds “by telling them they get a schedule with the estimate whether they ask for it or not. You cannot accurately determine construction overhead without one.”

“There has been an interesting by-product from these early-stage design estimates that we have completed,” says McNutt. She finds that the back-and-forth exchange between estimator and designer regarding project questions and challenges stimulates ideas to improve constructability. “We hear from clients when we submit our ‘Estimate Peer Review Memo’ that this process generates more than just an estimate.”

Market Rates

Keeping abreast of material price fluctuations is an ongoing priority. “Not a day goes by when we are not keeping tabs on market conditions,” says McNutt. What is the current cost of a cubic yard of concrete in this area? What is productivity like in Baton Rouge, La., versus Boise, Idaho? What is the price of lumber in Boston? Market conditions are influenced by a myriad of variables, and KMC aims to quantify what the market costs are on a given day. “Then we address the unknowns as part of our risk-contingency matrix,” McNutt says.

> **“Not a day goes by when we are not keeping tabs on market conditions.”**

“We continue to stay in touch during construction to validate the actual numbers and keep our pencils sharp,” she adds. “It is more challenging to keep up with changing prices when you are not working for a contractor, but it is essential to what we do.”

Project Delivery Models

KMC assists public agencies and design firms in the four primary project delivery models used today. For design-bid-build and design-build contracts, KMC typically serves as a supporting member of the design team. The firm provides constructability and construction scheduling services along with budgetary estimates for different alternatives as the design is being developed.

When the owner chooses construction manager/general contractor or progressive-design-build project delivery models, KMC plays a different role. “We work with public agencies directly in a more formal capacity to provide impartial cost estimates independent of the contractor,” says Salamie. In these procurement models, the team selected


When the 22nd Street Bridge cast-in-place concrete segmental bridge in Tucson, Ariz., was awarded as an alternative delivery construction manager/general contractor project, Kelly McNutt Consulting performed the independent construction estimate for the owner. Figure: City of Tucson.

The two concrete towers, one in Windsor, Ontario, and the other in Detroit, Mich., for the Gordie Howe International Bridge are approximately 722 ft in height. Each tower is composed of two pylons, which give the structures the shape of an inverted "Y". The top third of each tower houses the cable-stayed system that supports the bridge deck. Photo: Kelly McNutt Consultants.

submits their bid as a sole source, with no other contractors challenging their numbers. KMC provides that parallel estimate to ensure that the contractor is providing a fair price.

High-Profile Projects

McNutt says that KMC's work on construction estimates and constructability reviews for complex bridges has led to invitations from public agencies to support negotiations with contractors on major change orders. Being able to provide a client with a contractor's perspective goes a long way to understanding how to negotiate change orders.

Working with the Harris County, Tex., Toll Road Authority and designer COWI, KMC assisted with complicated change orders for the Sam Houston Tollway Ship Channel Bridge, which has 514-ft-tall pylons. KMC provided a complete bottom-up, independent estimate of the precast concrete segmental, cable-stayed bridge that was under construction. This estimate provided the agency with the backup information needed to move forward.

KMC provided services, including independent estimates, construction scheduling, and construction management support, for Parsons Transportation Group on the 1.5-mile-long Gordie Howe International Bridge project between Detroit, Mich., and Windsor, Ontario.The project is being delivered by a design-build contract with a portion funded by a public-private partnership. The cast-in-place concrete towers of the cable-stayed bridge are 722 ft tall. The tower legs, or pylons, are constructed with jump-form systems and give each tower a distinctive inverted-Y shape.

Most of the KMC staff is based in the Northwest, and they often have personal ties to projects in that region. One employee worked on the concrete segmental bridge construction of the West Seattle Bridge in the 1980s, and was involved again in the estimating and access planning for the West Seattle Bridge emergency repair project after the bridge was closed in March 2020. (See the Spring 2023 issue of *ASPIRE*® for more on the West Seattle Bridge emergency repair project.) Employees who live in Portland, Ore., and Vancouver, Wash., have a personal interest in the Interstate 5 over the Columbia River project. The consultants' project knowledge and the relationships they developed over the years are helpful in bringing value to the design team and clients during early development decisions.

KMC provided the constructability review and independent construction estimate for the 22nd Street Bridge in Tucson, Ariz. This project, which was awarded as an alternative delivery construction manager/general contractor project, involves widening the existing 22nd Street from Kino Parkway to Tucson Boulevard and includes two new cast-in-place concrete segmental bridge structures with three lanes in each direction. KMC worked directly for the City of Tucson and had no bias toward any particular type of structural solution.

The replacement of the Shoemaker Bridge in Long Beach, Calif., will be an iconic cable-supported structure over the Los Angeles River. Working for lead designer HDR, KMC is providing early-stage construction scheduling and estimating for this signature structure.

Teamed with Stanton Constructability Services, KMC will provide independent construction estimates and constructability review input on two major cable-stayed bridge projects in

Kelly McNutt Consulting (KMC) worked with WSP on the emergency rehabilitation of the West Seattle Bridge in Seattle, Wash. KMC provided an independent construction estimate for the retrofit project. Photo: Kraemer North America.

Cincinnati, Ohio: the Brent Spence Bridge and the Western Hills Viaduct. The Brent Spence Bridge spans the Ohio River along Interstate 75 and connects Ohio and Kentucky. The northernmost stretch of the Brent Spence Corridor project will connect to the Western Hills Viaduct Replacement bridge via a new interchange. The current Western Hills Viaduct is more than 90 years old and is at the end of its useful life. The proposed replacement is a single-deck extradosed bridge supported by two pairs of cable-stayed towers. The new bridge will reside 50 ft south of the existing viaduct, which will remain in place and continue to carry traffic until its replacement is finished.

Managing Risk

Since its founding, KMC has witnessed the precipitous rise in the cost of bridge construction. On large high-risk, technical bridge projects, many contractors are taking a more conservative approach toward risk. The number of qualified bidders is decreasing, and prices are escalating above the current inflation rates. Owners are looking for input on market conditions and risk allocation to better understand and manage the cost of their major programs.

A common concern among agencies is how to manage financial risk and alleviate costs associated with infrastructure projects. According to Salamie, it is only natural for clients to want to pass on as much risk as possible to the contractor. However, that comes at a price, especially for design-build projects of high risk. KMC has helped clients develop a more equitable division with the contractor to reduce their risk profile.

KMC focuses on the basics: supporting clients with highly talented estimators, construction managers, and schedulers. In just a few years, the firm has achieved a national reputation for providing valuable services on complex bridge projects.

History of Kelly McNutt Consulting

Established in 2020, Kelly McNutt Consulting LLC (KMC) is certified in six states as a Disadvantaged Business Enterprise, Women-Owned Business Enterprise, and Small Business Enterprise. Although the firm is young, KMC's employees have decades of experience in heavy civil construction management, including bridge, highway, tunnel, marine, and transit work. While many employees work from home, KMC has a home office in Vancouver, Wash.

Kelly McNutt started in construction as a teenager working in the family contracting company. She earned a bachelor's degree in construction management from Washington State University and apprenticed with Washington State University Facilities Services Operations. After graduation, she was employed by a well-known construction firm and had the opportunity to work on a variety of projects. That experience helped McNutt gain a deep knowledge of the industry and build great professional relationships, which were to be the foundation for her business.

When KMC was founded, the construction market was characterized by labor shortages and unstable material prices, and transportation agencies and designers were often finding that their internal estimates no longer matched contractor bids. "Kelly was in the right place at the right time," recalls Ralph Salamie, senior manager and director at KMC. "Not only did she assemble a team of talented and experienced engineers who have made their careers building and estimating complex infrastructure projects, but she chose the right time to do so."

The KMC team continues to add depth and technical expertise. The firm has expanded from 4 to 24 people, and repeat business is the hallmark of their success.

Reference

1. Strawberry, B. 2019. "FMI Corporation 2019 North American Megaprojects." https://fmicorp.com/uploads/media/FMI_N-American_Megaprojects_2019.pdf.

The Benefits of BIM for Bridge Design and Construction

by Roy L. Eriksson, Eriksson Technologies Inc.

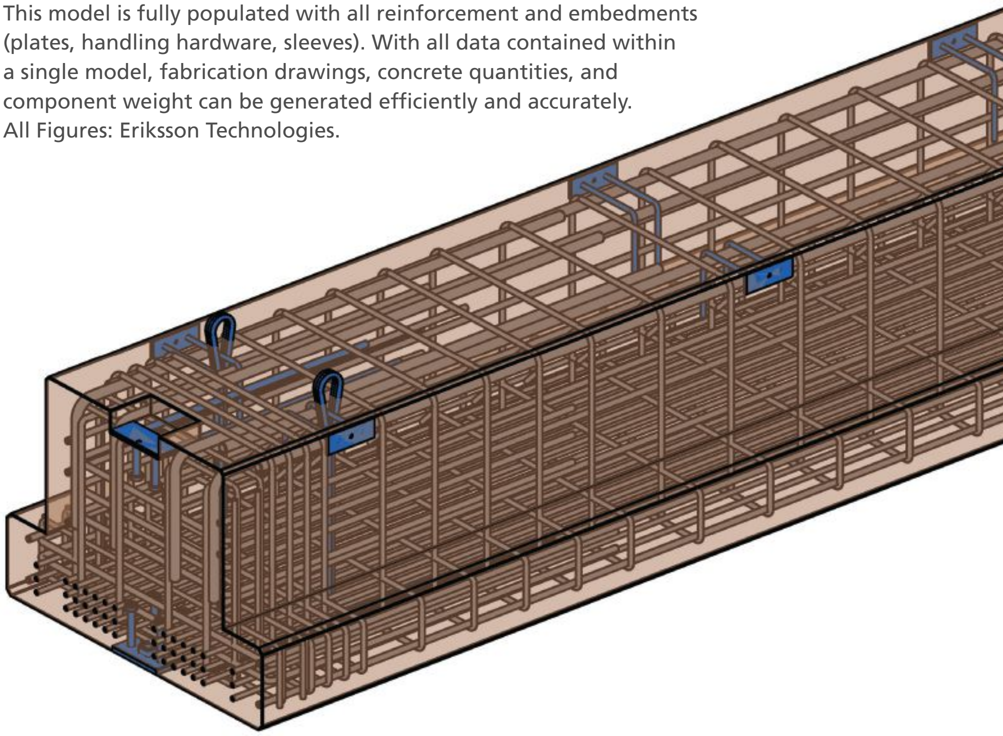
The use of building information modeling (BIM) has become widespread in the world of commercial structures. Entire projects are being planned, designed, and delivered using BIM technology to great success. BIM is no longer viewed as a novel or alternative way of delivering projects. The benefits realized and the efficiencies gained by its full integration into project workflows have made it indispensable for project delivery. In our practice, we have seen firsthand what BIM can do and, with several years of successful experiences, we have embraced it with open arms.

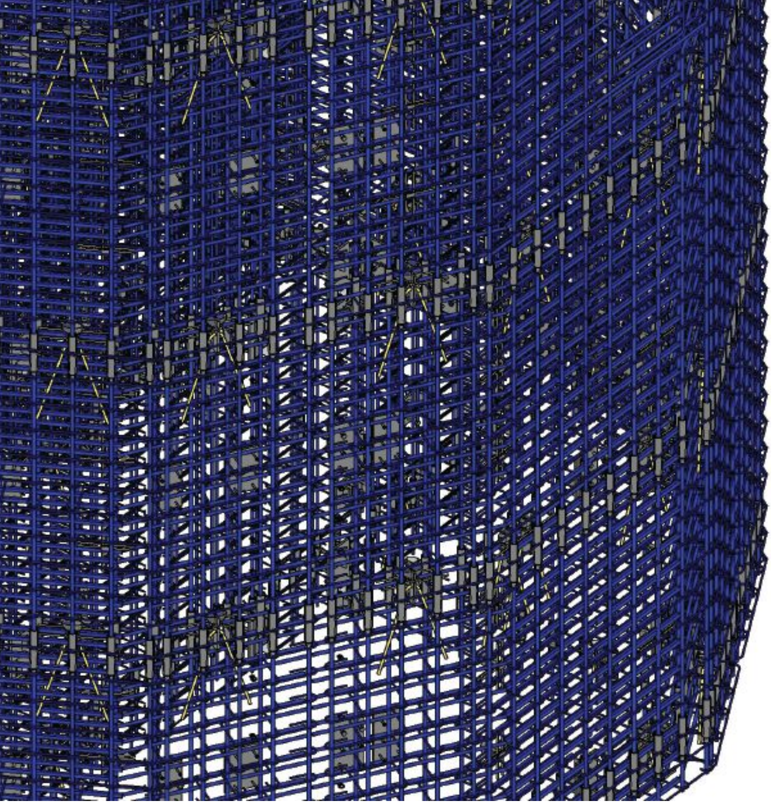
However, BIM implementation in bridge design and construction is still in its early stages. Relatively few projects have been delivered end to end using BIM. The transportation agencies that are making progress in its adoption seem to be focusing first on delivering contract documents as a three-dimensional (3-D) model rather than as a conventional set of 2-D drawings. This, of course, is a necessary early stage of BIM delivery, but it barely scratches the surface of BIM's full potential. Some consulting engineering firms are making progress implementing design in BIM, but they seem to have not yet found firm footing in delivering the type of information needed to construct a bridge structure or fabricate the individual structural components (such as precast concrete girders).

The timeline of a BIM model can cover every phase of the project, beginning as early as the conceptual phase of bridge design and extending all the way to the end of the bridge's useful life. From a practical point of view, the useful model begins once the basic type of bridge has been established. The geometry of the bridge comes first, followed by structural framing and preliminary structural component type and size selection. BIM modelers typically create the model, and once sufficient detail has been included, bridge engineers can begin their work of analyzing the structure and designing the structural components. Detailing follows, as reinforcement and structural embedments and attachments are designed, detailed, and added to the model. Other stakeholders can now begin to interface with the model and add their enhancements, such as lighting, drains, and so forth. At this point, the model starts to become a comprehensive repository for all the information about the bridge, and is now referred to as a federated model. The model is the nonredundant central repository for data, also known as the "single source of truth." All stakeholders must ensure that there are no conflicts within their parts or between their parts and other stakeholders' parts. The BIM manager for the overall project should ensure that all stakeholders have done their jobs.

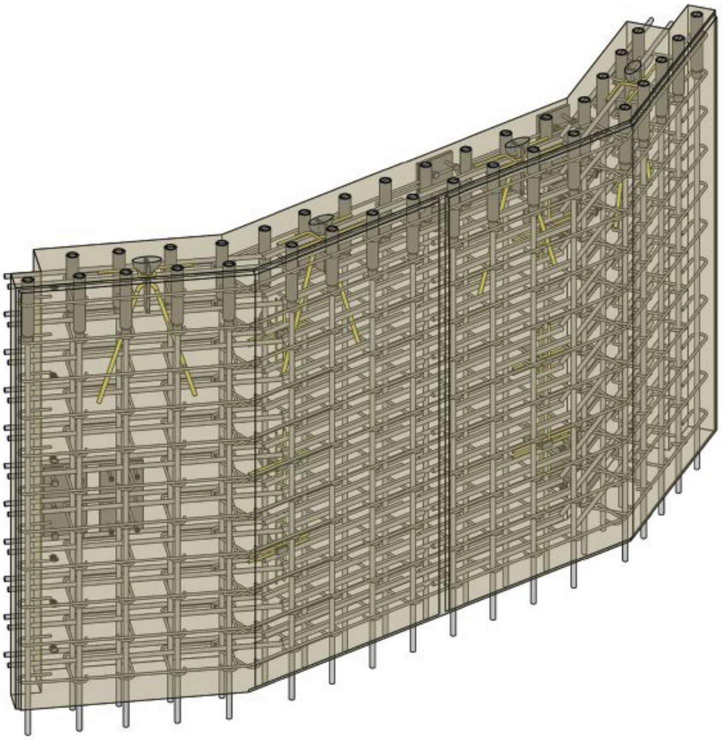
Design, of course, is an iterative process. But the design process using BIM is greatly enhanced and many benefits are realized because all the data for a bridge are found in a single location. Conflicts between objects in the model

A BIM model of a precast, prestressed concrete inverted-tee beam. This model is fully populated with all reinforcement and embedments (plates, handling hardware, sleeves). With all data contained within a single model, fabrication drawings, concrete quantities, and component weight can be generated efficiently and accurately. All Figures: Eriksson Technologies.





Partial elevation of a complex, densely reinforced precast concrete tower. With reinforcement, embedded handling hardware, and connections, the detailing of total-precast concrete structures can be challenging using conventional means. However, BIM was used from start to finish on this project to deliver it virtually error free.



Elevation of a single, fully populated precast concrete panel of the tower (partial elevation view shown in the left figure). During erection, BIM is used to ensure that reinforcing bars extending from the bottom of the panel slide precisely into the grout sleeves in the panel below (not shown).

can be detected early and quickly, and can be efficiently fixed. Contrast this with a conventional design workflow, where a problem might not be noticed until the bridge is under construction. The cost of fixing a problem in virtual space where, for example, two objects occupy the same position (referred to as a clash) is trivial. However, the cost of fixing a clash at the jobsite can be extremely high. As we all know, with field problems there is not only the obvious cost of labor and materials but also the time expended determining a solution and the resulting impact on the overall project schedule.

With design centered on a 3-D model of a bridge, new doors open to radically improve safety, accuracy, and quality of design. Technology is available to create two-way connectivity between engineering design software and BIM models. There are no longer two separate models—one for design and one for a "drawing"—just one 3-D model. Software can do a lot of the heavy lifting associated with creating and finalizing a design. Tools can be created to assist the designer with bridge geometry, component selection, component sizing, reinforcement design, the layout of reinforcement, and other detailing tasks. Traditionally, this process has been called automated design, but in recent years has been eclipsed by artificial intelligence, which is broader in scope and deeper in complexity. There seem to be no hard limits on the ability of computer hardware and software to perform every aspect of the design. The human/cyber team can take projects to completion faster, more accurately, and more cost effectively than ever before.

Fabrication support is one aspect of designing and detailing total-precast concrete commercial structures where BIM has proven to be invaluable. The structural components for these types of structures are precast, prestressed concrete components fabricated in plants. Detailed fabrication drawings and bills of materials are required, and accuracy is an all-important concern. There is simply no room for error. Humans can perform this work, but it is tedious and has potential for error if done manually. This is the type of work at which computers excel.

BIM tools can generate detailed, ready-to-fabricate piece drawings and bills of materials for all the structural components and connections in a project. Projects delivered in this manner typically yield efficiency gains exceeding 25%, which translates to a minimum 25% reduction in total labor costs to design and fully detail a project. BIM technologies have also been applied to bridge projects that use precast, prestressed concrete components, such as bridge girders, deck panels, pier caps, piers, piles, and other precast concrete product types.

For more than two decades, government entities such as the Federal Highway Administration and the National Cooperative Highway Research Program have made substantial investments that have laid the groundwork for implementing BIM in transportation. Most of this work has been to develop formats and open standards for data interchange. That's certainly a good start, but BIM now needs to be implemented industrywide. Going forward, we see a good parallel between BIM implementation in the commercial and bridge worlds. At Eriksson, we are dedicating serious resources to BIM delivery for bridges. Others are too. We expect that this will increase the pace of BIM adoption for bridges at an increasing rate going forward.

Thoughts about Durability and Service-Life Design of Bridges

by Dr. Elizabeth I. Wagner and Dr. Michael C. Brown, Wiss, Janney, Elstner Associates Inc.

Structural design of bridges has evolved over the last century, transitioning from allowable stress design to load factor design to load- and resistance-factor design (LRFD).[1] Currently, the design of new bridges includes a heightened focus on designing for durability. More and more, owners are requiring that bridges be designed with durability in mind, with specifications commonly calling for bridges to achieve service lives of 75 or 100 years—and sometimes beyond.

Service Life versus Design Life

What does it mean to achieve a 75- or 100-year service life and how is that different from the 75-year design life in the Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*?[1]

Just as the objective of structural design is for a structure to continue to support anticipated loads over its *design life*, the goal of durability design is for the structure to remain serviceable under anticipated environmental exposures for its *service life*. A structural design may consider changes in loads over time resulting from construction, service loads, or extreme events, and may also consider changes in the capacity or strength of the component due to concrete curing, creep, or fatigue. Similarly, a durability design must consider changes in environmental exposures and in material properties and conditions due to deterioration over time. Designing according to the AASHTO LRFD specifications or a similar structural design code is intended to result in a bridge that will continue to meet minimum strength and serviceability requirements over its design life (typically 75 years). However, these codes have traditionally been developed as a minimum structural safety requirement and do not guarantee that the materials or ancillary components (such as joints and bearings) will be able to provide that strength and serviceability for that same design life. The industry has come to recognize that design for durability is needed, such that the combination of materials, design details, construction practices, and planned maintenance activities will enable the bridge to achieve its target service life.

In the context of durability design, end-of-service life is defined as the time at which deterioration exceeds a particular limit, which must be specified. Simply stating "design for a 100-year service life" does not clearly define the requirements. For example, when the service life of a component (such as a bridge deck or pier cap) is limited by corrosion of the reinforcing steel, the target service life might be defined by the time at which corrosion would be expected to first initiate in the reinforcing steel, the time at which corrosion would first cause damage (such as cracks, delaminations, or spalls) to the concrete, or the time at which corrosion-related damage would affect a certain percentage of the component's surface and require structural repair. When service life is limited by other types of deterioration, such as cyclic

Twin core holes from a reinforced concrete bridge deck. The crack on the right is aligned with reinforcement. Materials, design details, construction practices, and planned maintenance activities will enable a bridge to achieve its target service life. All Photos: Virginia Department of Transportation.

A built-up asphalt and sheet membrane being placed on a highway bridge deck as part of a deck rehabilitation. Planned maintenance activities are an important aspect of a bridge durability plan.

freezing and thawing or alkali-silica reaction (ASR), the specific limit may be more difficult to define in quantitative terms. In such cases, the target service life may instead be defined as the time at which deterioration of the concrete due to any of these mechanisms occurs, or occurs to such an extent as to affect the structural capacity of the component.

Durability is affected by both the macroenvironment where the structure is located and by the microenvironment of individual components within the bridge. Just as with the AASHTO LRFD specifications, different limit states may, and often do, apply to different components within a single structure. For example, a buried component such as a pile will have different exposure and may have a lower threshold for allowable damage at the end of service than a bridge deck; if the thresholds vary, it is because the structural importance of components differs, and identification and remediation of deterioration is much easier for a bridge deck than it is for a buried pile. Likewise, different structural components may also have different target service lives, with replaceable components such as bearings and joints often having shorter target service lives than nonreplaceable components such as substructures and abutments. In some cases, it may not be possible for a component to achieve the overall target service life, and replacement of that component (for example, a joint, bearing, coating, or wearing surface) will need to be considered in the structural design as well.

Designing for Durability

How does one design for durability and a target service life? Once the end-of-service criteria have been defined for a bridge and its individual components, the durability engineer will examine the components and their environmental exposures, identify the relevant deterioration mechanisms, and develop a protective strategy to provide confidence that each component and the overall structure will achieve their target service lives.

There are several approaches for developing a protective strategy

Definitions

Design life—The period of time on which the statistical derivation of transient loads is based; this period is 75 years for the AASHTO LRFD specifications.[1]

Target service life—The assumed period of time the bridge is expected to remain in operation, without rehabilitation or significant repair, and with only routine maintenance (intended life). This maintenance would include replacement of renewable elements.[2]

A combination of carbon, epoxy-coated, and galvanized steel reinforcement at the intersection of bridge superstructure components prior to concrete placement.

for durability, and typically a combination of approaches will be used. For deterioration mechanisms whose physical principles are well understood, such as corrosion, service-life modeling can be used to predict the most *probable* service life for the component. The modeling will consider options for materials (such as reinforcement types and concrete mixture proportions), component details (such as reinforcement cover and geometric configuration), construction practices (such as tolerances and placement and curing methods), and planned maintenance activities (such as reapplication of coatings and sealants, repairs, and overlays). In this way, multiple protection strategies can be efficiently examined, and the strategies most likely to achieve the target service life can be presented to the structural designer and owner for consideration.

For other deterioration mechanisms that cannot currently be modeled, such as deterioration due to freezing and thawing or ASR, development of a protective strategy will often rely on *avoidance* as an approach.[2,3] This typically entails laboratory testing to confirm that the materials used will resist or are not susceptible to a particular form of deterioration. In some cases, design teams rely on industry best practices and extensive empirical experience with specific design approaches to determine how to provide protection against certain deterioration mechanisms that are not practical or possible to evaluate in the laboratory. This approach is commonly referred to as *deemed to satisfy* in service life design guides.[2,3]

Durable Materials

How can we use durable materials and better construction practices now to avoid maintenance issues later? While the details of a particular protective strategy will be unique to the specific component and environmental conditions present, all protective strategies rely, to some extent, on the durability of the materials selected.

Concrete may need to have low permeability to resist chloride and sulfate ingress, and low shrinkage potential to resist cracking. Service-life modeling can be used to determine the minimum performance requirements for concrete to achieve a specific service life with respect to corrosion, and laboratory testing can be performed on candidate concretes to confirm that these and other performance requirements can be achieved. A combination of low water–cementitious materials ratio and supplementary cementitious materials (SCMs) such as fly ash, slag, or silica fume may be needed to provide sufficiently low-permeability concrete to achieve a 75- or 100-year service life, and these mixture proportions can have additional benefits with respect to mitigating other types of material degradation, such as sulfate attack or ASR.

For certain environments and structures, corrosion-resistant reinforcement may also be necessary to achieve a 75- or 100-year service life. Coated steel reinforcement such as epoxy-coated or galvanized bars can delay the time to corrosion initiation compared with uncoated black steel. Uncoated low-carbon chromium and stainless steels can resist more aggressive concentrations of chloride ions compared with uncoated black bar—but we must be mindful that there are many different grades of such steels with different mechanical and corrosion-resistant properties. Nonmetallic reinforcement, such as glass-fiber-reinforced-polymer composite or carbon-fiber-reinforced-polymer bars, can also be used as an alternative to steel reinforcement, but its use may require special consideration for structural design and fabrication.

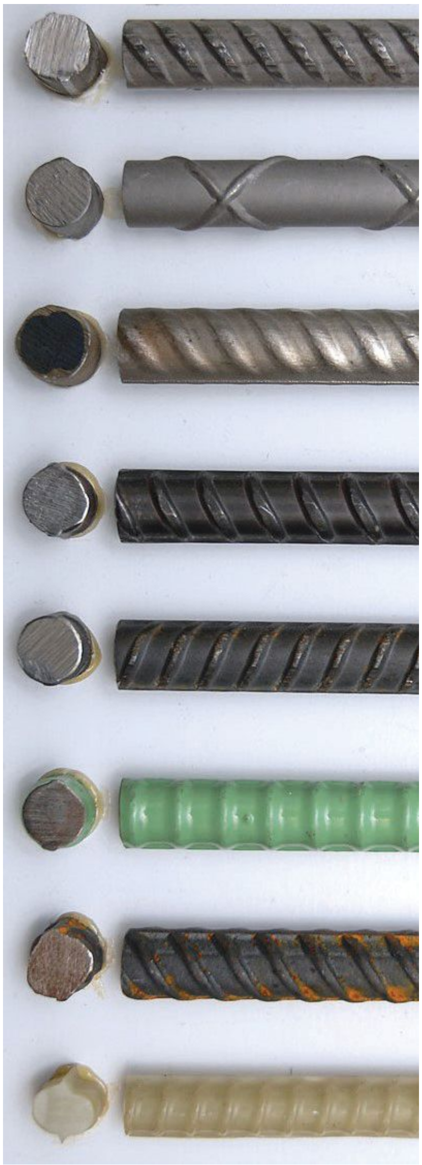
One challenge that may be encountered when designing structures for durability is the potential trade-off between short-term strength and long-term durability. The proportions of cementitious materials in a concrete mixture can be increased to achieve high early strengths, but these changes may increase shrinkage and cracking potential. Also, the high dosages of SCMs that are sometimes needed to achieve the target durability characteristics may result in slower strength development and therefore extended construction schedules. Durability engineers can work with designers and contractors to balance the need for timely strength gain with the competing need for long-term durability.

What about the Details?

Using durable materials is key to achieving long service lives; however, without proper design details, a structure may still not achieve its target service life. If the cover over reinforcement is too shallow, it may not provide enough concrete to protect the reinforcement from corrosion, whereas too much cover may increase crack widths and provide a more rapid pathway for chloride and

Different types of reinforcement. Shown from top to bottom are:

- Stainless steel 316LN
- Stainless steel 304
- Stainless steel clad carbon steel
- Low-carbon chromium steel
- Low-alloyed duplex stainless steel 2101
- Epoxy-coated carbon steel
- Carbon steel
- Glass-fiber-reinforced polymer



other contaminants to enter the concrete and reduce its durability.

Just because a bridge is designed for a 100-year service life does not mean it is designed for no maintenance. A bridge may have all the right concrete materials, reinforcement type, and design cover to resist deterioration over the design service life, but if the deck drainage system fails and causes runoff to flow onto the pier cap and substructure, or if the joints lock and cause the adjacent concrete to spall, then unanticipated deterioration may reduce the service life of the structure. Good quality control during construction and routine inspection and maintenance are important to achieving service life and should be part of any durability plan. Designing for durability should also facilitate access for inspection and consider replaceable components.

What More Is There to Know?

Durability has become an increasingly important consideration in the design of new bridges, with guidance recently published by AASHTO facilitating its incorporation throughout the industry.[2] (See the FHWA article on service-life design on page 62.) Nonetheless, the industry would benefit from a better understanding of physical principles for many of the modes of deterioration affecting bridge components, and the development of suitable models for these types of deterioration. In addition, the rapid evolution of construction materials coupled with changing climate and exposure conditions have the potential to affect service life in unexpected ways. Yet, with an added focus on durability, we can now aspire to develop structures that can withstand these uncertainties and achieve service lives of 75 or 100 years—or more.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.
2. AASHTO. 2020. *Guide Specification for Service Life Design of Highway Bridges*. Washington, DC: AASHTO.
3. *fib* (International Federation for Structural Concrete). 2006. *Model Code for Service Life Design*. *fib* Bulletin 34. Lausanne, Switzerland: *fib*.

Dr. Elizabeth I. Wagner is a senior associate at Wiss, Janney, Elstner Associates Inc. in Northbrook, Ill., and Dr. Michael C. Brown is an associate principal at Wiss, Janney, Elstner Associates Inc. in Falls Church, Va.

EDITOR'S NOTE

As discussed in this article, designing a structure and its components for a specific service life involves more than increasing concrete cover. Suitable knowledge of exposure conditions, deterioration processes, construction materials, and construction and maintenance practices is required to make sound choices during design. Case studies of designing for service life, including full probabilistic design, partial factor design, deemed to satisfy design and avoidance of deterioration can be found in in "International perspective: Extending the service lives of bridges," which appeared in the January–February 2008 issue of PCI Journal. *https://doi.org/10.15554/pcij.01012008.121.142.*

Finding Creative Concrete Solutions at LAX

Designing the Automated People Mover at Los Angeles International Airport to reduce traffic impact and meet seismic resiliency requirements

by Chester Werts and Rob Richardson, HDR Inc.

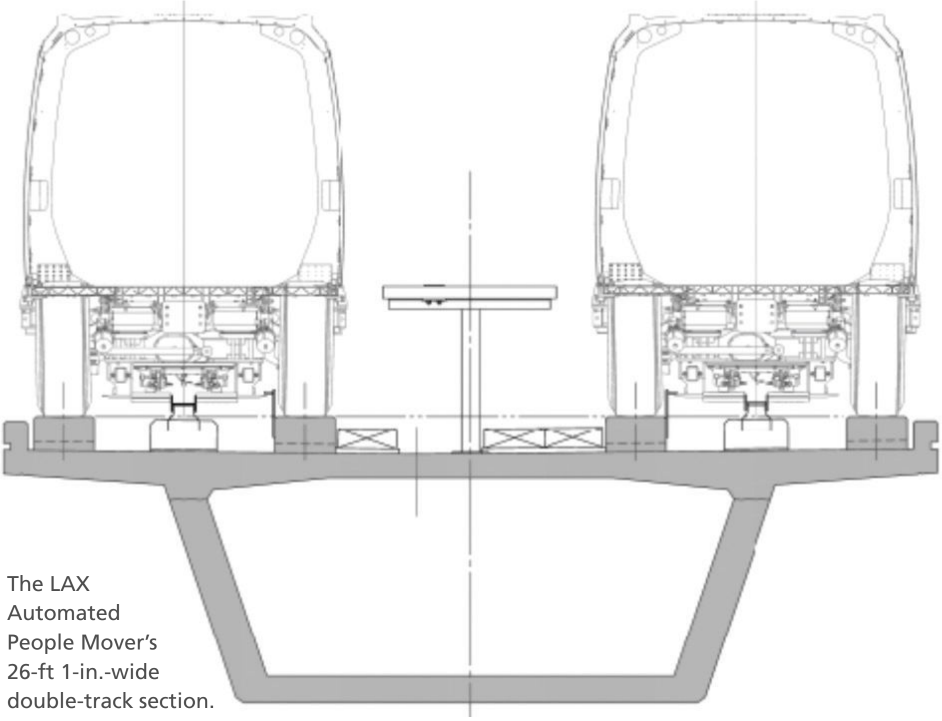
Los Angeles World Airports' (LAWA's) Automated People Mover (APM) at Los Angeles International Airport (LAX) will enhance the travel experience and provide a long-awaited connection to greater Los Angeles regional transportation systems. But designing and constructing more than 2 miles of elevated guideway at the world's fifth-busiest airport involves some complex challenges.

Most notably, the project requires that traffic be kept moving in LAX's Central Terminal Area—an extremely busy hub from which passengers arrive and depart. Furthermore, given the APM's Southern California location, engineers also had to ensure that the design would meet strict seismic resiliency requirements.

Project Overview

The $2 billion APM project—which includes the fixed facilities, systems, vehicles, and vehicle controls—is being built using the public-private partnership delivery method. The APM is the centerpiece of LAX's Landside Access Modernization Program and overall transformation. It will connect the airport to regional public transportation and provide dependable access to the terminals. It will also eliminate the need for shuttles to rental-car lots—a current source of traffic congestion—by connecting the airport to the new Consolidated Rent-A-Car (ConRAC) facility. The APM project includes 2.25 miles of elevated guideway, five passenger stations, two intermodal transportation facilities, and a maintenance and storage facility.

The guideway alignment weaves through LAX's Central Terminal Area and across State Route 1 at a deck height of approximately 65 ft before it turns across Century Boulevard and descends to a height of approximately 38 ft to remain clear of the runway protection zone. The alignment then turns sharply



The LAX Automated People Mover's 26-ft 1-in.-wide double-track section. Figure: HDR Inc.

profile

LAX AUTOMATED PEOPLE MOVER PROJECT / LOS ANGELES, CALIFORNIA

BRIDGE DESIGN ENGINEER: HDR Inc., Los Angeles, Calif.

OTHER CONSULTANTS: Geotechnical consultant: Group Delta; architecture and station design: HNTB; station design: Kleinfelder, IDS Group; guideway independent design checks: MGE Engineering, PacRim Engineering

PRIME CONTRACTOR: Fluor/Balfour Beatty/Flatiron/Dragados

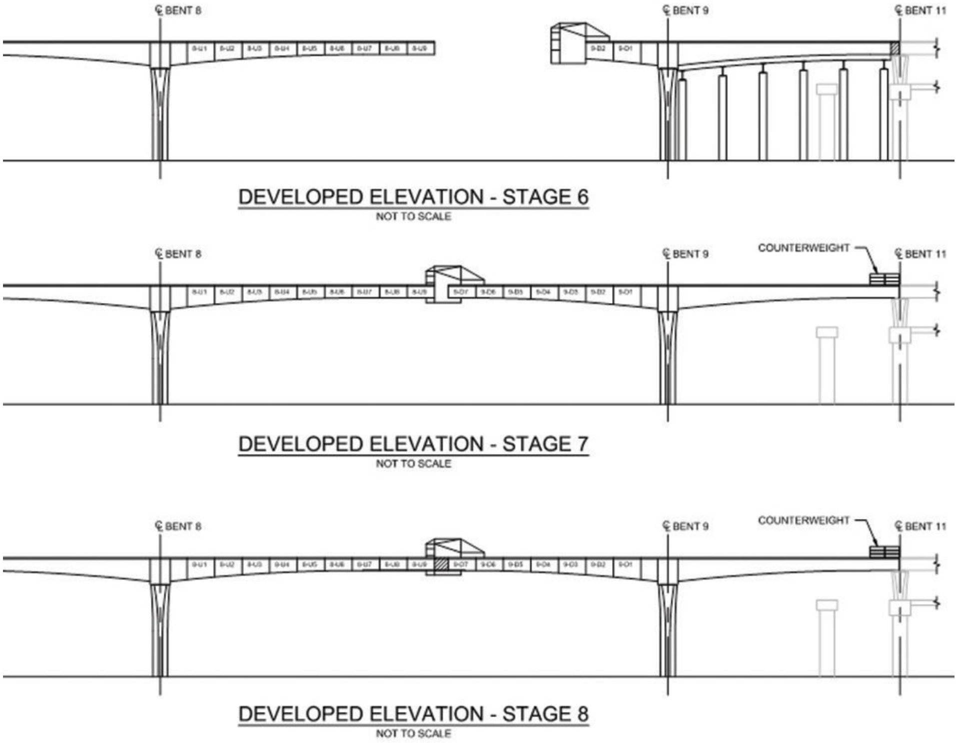
CONCRETE SUPPLIERS: CalPortland, Glendora, Calif.; Cemex, Inglewood, Calif.

OTHER MATERIAL SUPPLIERS: Bearings: RJ Watson, Alden, N.Y.; reinforcing steel: Integrity, Perris, Calif.; post-tensioning: DSI, Bolingbrook, Ill.

Nighttime view of form travelers being used during concrete segmental construction of the 212-ft span over Sepulveda Boulevard. Photo: Los Angeles World Airports.

to run adjacent to 96th Street, and the height increases to approximately 50 ft to meet the ConRAC station. Although divided into 11 segments for permitting purposes, there are actually 19 multispan bridge frames, with the longest frame nearly 1000 ft in length. Typical 140-ft-long spans have a constant depth of 7 ft, while longer spans are haunched, with a maximum depth of 13 ft at the pier for spans up to 277 ft.

The concrete segmental guideway is composed of two basic structure types. A 26-ft 1-in.-wide dual-track box girder makes up most of the guideway, but at every station there are two 21-ft



Stages of concrete segmental construction on a span that used form travelers. The concrete box girders of both back spans were cast in place on falsework. Form travelers were then used to construct the segments of the intermediate main span with a closure pour connecting the two cantilevers. Figure: HDR Inc.

LOS ANGELES WORLD AIRPORTS, OWNER

BRIDGE DESCRIPTION: 2.25-mile-long, 76-span (not including stations), combination single-track and dual-track cast-in-place concrete segmental box-girder structure

STRUCTURAL COMPONENTS: Superstructure consists of 21-ft 0-in.-wide single-track and 26-ft 1-in.-wide dual-track cast-in-place post-tensioned concrete box-girder sections. Substructure is cast-in-place concrete single-column bents ranging from 6 to 9 ft in diameter, flared at the top to match the superstructure side slopes, and two-column straddle bents in limited locations where required. Columns are supported on 107 cast-in-drilled-hole piles, ranging from 8 to 11 ft in diameter.

The guideway under construction in front of the iconic Los Angeles International Airport theme building. Note the expansion joint visible in the guideway at the pier. Photo: HDR Inc.

0-in.-wide single-track box girders, one on each side. Transition spans are used to connect the two girder types. Almost all concrete segments are post-tensioned; however, only conventional reinforcement is used in a few areas. Including all frames of dual-track and single-track box girders within the elevated guideways, there are 76 spans, with additional single-track box-girder spans within the station structures.

The guideway superstructure is mostly composed of concrete post-tensioned box girders constructed on falsework, but four spans were constructed using a form traveler (with the back span segment cast on falsework). Post-tensioning for the conventional box girders consists of draped tendons in the webs; there are typically three tendons in each web, with nineteen 0.6-in.-diameter strands per tendon. For the concrete segmental spans constructed using form travelers, tendons are located in the top and bottom slabs. The hybrid approach of concrete segments cast-in-place using form travelers and cast-in-place on falsework provides an unusual post-tensioning layout in which three pairs of cantilever tendons in the deck transition over the piers to provide draped post-tensioning in the back spans.

View of the guideway under construction. The guideway elevation varies to provide clearance over streets and buildings while maintaining the Federal Aviation Adminstration's overhead clearance requirements. Photo: HDR Inc.

The substructure generally consists of architecturally flared circular columns founded on drilled shafts of up to 11 ft in diameter. Single-column bents are used for most of the guideway, but there are also two-column straddle bents where single-column bents were not feasible. The maximum height of the columns is approximately 60 ft and occurs in the Central Terminal Area, where the elevated guideway is at a constant elevation of 168.50 ft. In the east half of the project, the guideway descends to an elevation of 137.17 ft to maintain airspace clearances.

Design on the first segments began in early 2018, with construction beginning in mid-2019. Concrete for the last elevated section was placed in April 2022, and all guideway segments are now constructed. In a span of more than two years (and during a pandemic),

AESTHETICS COMMENTARY

by Frederick Gottemoeller

It is such a pleasure to see a large and complex project developed as a consistent assembly of compatible and interlocking parts, each contributing to a high-quality result, no matter where it occurs in the project. Because of the complex configuration of the people mover system, the intricate needs of existing traffic, and the seismic redundancy required, the Los Angeles International Airport (LAX) Automated People Mover presented a plethora of challenging design issues. Too often, such projects are addressed by optimizing the individual solutions for each group of challenges and then mashing together the whole agglomeration of solutions and living with whatever the final assembly looks like.

At LAX, the parts begin with the post-tensioned concrete box girders supporting the tracks. They all look similar to each other, regardless of whether they support one track or two, what their spans are, or whether they were cast in place on falsework or using form travelers. The torsional stiffness of the box form minimizes the distracting details, brackets, and fittings often required to address complex structural situations. If a box must be deeper to accommodate a longer span, the basic box shape stays the same—its webs are simply extended. All the piers resemble each other, too. They are round shafts that flare smoothly to blend into the box girder above, regardless of the box width or whether it is haunched. Even at the stations, the piers all look the same.

All these smooth and streamlined shapes are made of the same light-colored concrete. The mass of the concrete dampens noise and vibration, and the light color and smooth surfaces keep the spaces below bright and pleasant. The Automated People Mover visually unifies the whole LAX terminal area. Wherever you are among the terminals, the system adds functionality and attractiveness to its immediate surroundings. I don't get to Los Angeles often, but I'm tempted to make a trip just to enjoy this new facility.

The guideway's sweeping alignment offers travelers remarkable views of the iconic theme building. Photo: HDR Inc.

nearly 70,000 yd^3 of concrete were placed. Installation of appurtenances (such as the steel guide beam that will direct the vehicles on the guideway), switches, and other equipment continues on top of the guideway as of this writing. Operational testing of the vehicles on the system is expected to be initiated in phases, starting in 2023 with the track that connects the maintenance and storage facility and the ConRAC.

Concrete Segmental Construction

The biggest challenge on this project was completing construction in the Central Terminal Area while maintaining traffic. One major solution involved cantilever construction using form travelers to span over buildings and major roadways, where falsework was either prohibited or impractical. These four cast-in-place concrete segmental spans range from 196 to 277 ft and cross two major roadways, Sepulveda Boulevard and Century Boulevard at the entrance to LAX, as well as an existing parking structure within the Central Terminal Area.

The use of concrete segmental construction allowed traffic to continue unimpeded on these important roads even as the guideway was being constructed. No falsework or temporary supports were constructed within the right-of-way, and all traffic lanes remained open. The parking structure, which had initially been expected to be demolished and rebuilt as part of construction, was instead preserved for continued use throughout construction. This concrete segmental work was built using a relatively uncommon hybrid construction method that incorporated balanced-cantilever concepts. All the segmental spans incorporate one cast-in-place concrete segmental span with cast-on-falsework back spans. For example, the span over Sepulveda Boulevard was built with 12 cast-in-place concrete segments, each about 15 ft long, and completed with a 7.5-ft closure pour. As each segment was formed, cast, and cured, the segment was post-tensioned, and then the form traveler moved ahead to construct the next segment. The original design assumed a single traveler would be used; however, to speed construction, the contractor used two travelers.

This hybrid construction method required extra attention to construction loads imparted on the structure, as well as permanent built-in forces. For example, after falsework in the back spans was removed, there were large dead-load moments in the columns supporting the concrete segmental span. These dead-load moments in the columns gradually reduced as cantilever construction continued. By the end of cantilever construction at closure, the change was so great that the net direction of the moment reversed at the top of the columns, leaving a built-in moment that had to be accommodated in the design.

Each stage of the work required detailed structural analysis, with interim phase calculations for each step of the process. Beyond dead-load reactions, other effects such as creep and shrinkage and locked-in erection forces also needed to be considered. These effects were mitigated by adjustments to variables such as the timing of falsework removal, and by physically jacking the superstructure closure apart on one of the guideway spans before placing the closure segment.

Seismic Resiliency

The guideway is located in one of the areas with the most earthquake activity in the United States, so the design had to comply with strict requirements for seismic resiliency. The design accounted for multiple levels of seismic events with specific performance requirements at each level. The two-level approach included designing for an operating design earthquake with strains limited to provide essentially elastic behavior, and also designing for a 2500-year maximum design earthquake with steel and concrete strains reduced from California Department of Transportation standards so that only repairable damage occurs. Accelerometers positioned at two locations along the guideway monitor seismic activity and trigger action in the APM system depending on the severity of seismic activity.

In the event of an emergency stop and shutdown, wherever possible, passengers traveling in a vehicle on the guideway will be taken to the nearest station to safely disembark. Elevated emergency walkways are provided along the entire guideway length so that emergency responders can escort passengers to safety on foot in the unlikely event that a train cannot get to a nearby station.

Designing the system to meet all these seismic requirements was a challenging task, complicated by the guideway's complexity—its significant horizontal curvature, varying elevations, the multiple combinations of segment structures and supports, and segments that abut stations. The resulting unconventional behavior and complex displacement profiles meant that a typical inelastic static analysis was not sufficient to predict the structure's displacement capacity. Instead, designers used a multimodal, inelastic pushover-analysis technique that incorporates contributions of multiple seismic modes and associated modal displacements. This led to an inelastic pushover analysis that mimics the displaced shape profile from a response spectrum analysis and allowed the designers to better understand the structure's performance in the design seismic events. This understanding provided the basis for the engineers to design and detail the critical structural elements to meet the project's stringent seismic resiliency criteria.

Other Challenges and Considerations

While the concrete segmental construction and seismic considerations were major challenges, the project team also overcame numerous other challenges. For example, with a congested site and limited right-of-way, choosing locations for the columns was an early task that proved to be daunting. The selected locations required careful consideration of span length and curvature to fit the guideway between and over existing parking structures, the airport's iconic theme building, future and active roadways and intersections, existing underground utilities, and more. As design progressed, designers also had to meet extremely tight tolerances on the guideway, especially from one bridge frame to the next. Specialized expansion joints were used on the running plinths as well as the APM's guide beams and power rails. Limiting relative displacement between frames, especially under seismic loading, led to specialized bearing details to accommodate combined shear and uplift. Each bearing was custom made to meet the specific needs of the APM frame it supports.

Concrete design strengths were 4 ksi for the cast-in-drilled-hole piles and columns, 5 ksi for the typical box-girder superstructure, and up to 7 ksi for the box girders in the four spans constructed with form travelers. Mass concrete concerns were addressed by using a special concrete mixture that included Orca aggregate, which lowers the heat of hydration during curing by reducing the required amount of cement to create a high-performance concrete. Cooling tubes were also added in case the measured temperatures began to climb beyond acceptable levels.

Sustainability was another important consideration throughout the project. As work began, a large gathering of stakeholders, including representatives from LAWA, the design and construction team, and others, met to explore ideas and set a plan for encouraging sustainable design. That effort paid off as the project was honored in 2022 with an Envision Gold Award for Sustainable Infrastructure. The project was praised for minimizing light pollution, noise, and vibration, and improving the users' access to sustainable transportation options.

As the APM approaches completion, LAX travelers are becoming familiar with the gentle sweeping curves and clean uniform look of the concrete guideway. Once vehicle testing is complete, passengers will benefit from the new structure, which will provide a vastly improved experience for patrons of one of the world's busiest airports. A

Chester Werts is a senior design principal for HDR Inc. and is the engineer of record on the LAX APM project. Rob Richardson is HDR's West Region bridge leader and led the guideway design.

The guideway transitions from a highly efficient dual-track box section to independent single-track sections that straddle the stations. Photo: HDR Inc.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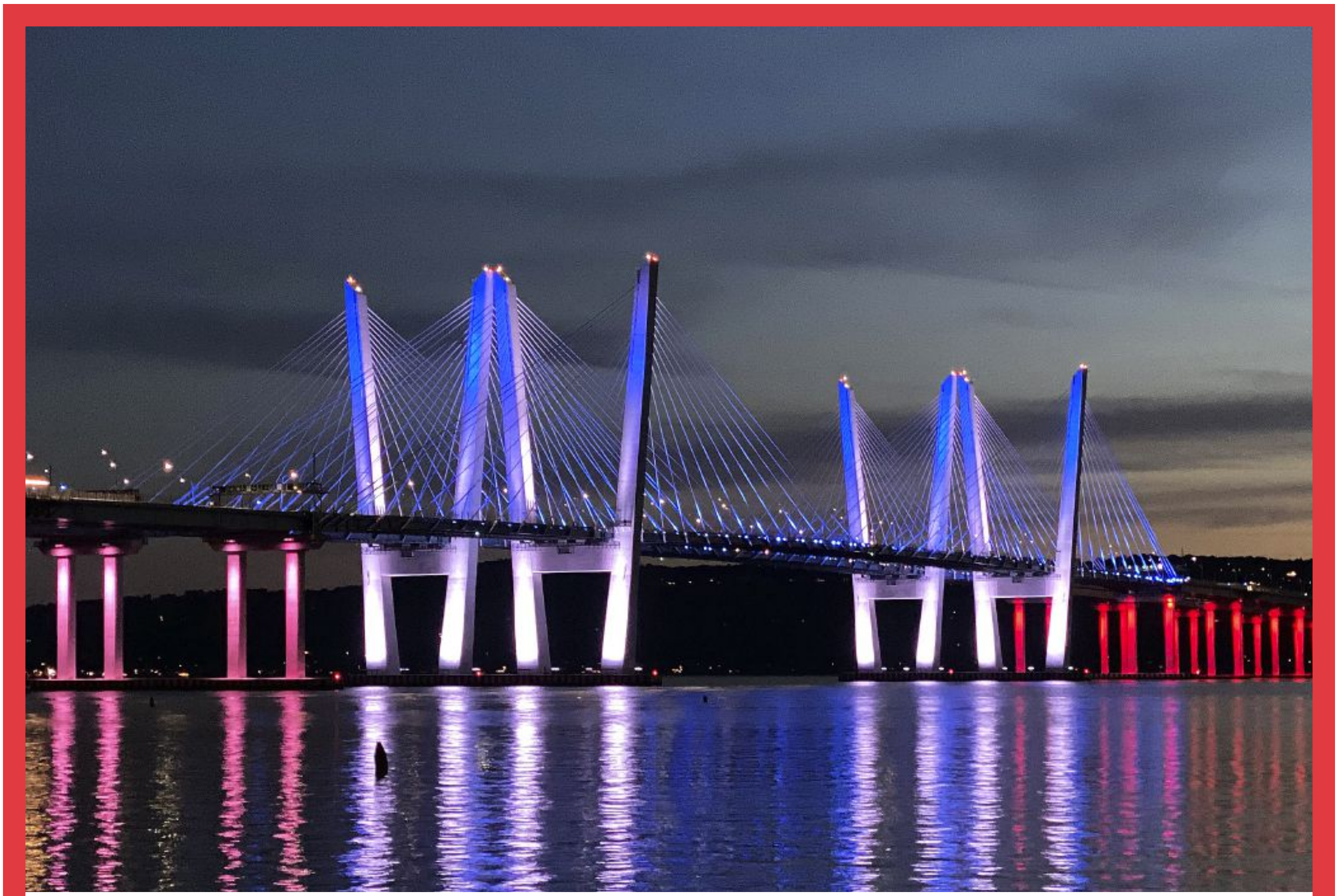


Harkers Island Bridge Replacement: NCDOT's First FRP-Reinforced Concrete Bridge

by Trey Carroll, Ashvin Patel, and Ahmad Ighwair, North Carolina Department of Transportation

For the North Carolina Department of Transportation's Harkers Island bridge replacement project, a new fiber-reinforced-polymer reinforced concrete structure replaces two 50-year-old bridges. Harkers Island can be seen in the background. Photo: Balfour Beatty.

The Harkers Island bridge replacement project is the North Carolina Department of Transportation's (NCDOT's) first bridge entirely reinforced with fiber-reinforced-polymer (FRP) reinforcing bars and prestressing strands. Harkers Island is located in Carteret County, N.C., near the southern end of the Outer Banks and adjacent to the Cape Lookout Lighthouse and Cape Lookout National Seashore. The bridge crosses a tidal area known as The Straits and is less than 4 miles from two ocean inlets. The $60 million design-bid-build project is 3200 ft long with 28 spans and features a navigational span with 125 ft of horizontal clearance and 45 ft of vertical clearance.

The bridge replaces two sequential 50-year-old bridges: the Earl C. Davis Memorial Bridge, which is a swing-span movable bridge, and Carteret County Bridge No. 96. Together, these structures have provided the only vehicular access and hurricane evacuation route for Harkers Island. The swing-span bridge is in poor condition due to severe corrosion deterioration, and mechanical issues can frequently prevent it from opening to commercial and recreational vessel

profile

HARKERS ISLAND BRIDGE / CARTERET COUNTY, NORTH CAROLINA

BRIDGE DESIGN ENGINEER: North Carolina Department of Transportation Structures Management Unit, Raleigh

CONSULTANTS: Roadway design: RS&H, Charlotte, N.C.; geotechnical engineering: S&ME Inc., Charlotte, N.C.

PRIME CONTRACTOR: Balfour Beatty Infrastructure Inc., Wilmington, N.C.

CONCRETE SUPPLIER: S&W Ready Mix, Clinton, N.C.

PRECASTER: Coastal Precast Systems LLC, Chesapeake, Va.—a PCI-certified producer

OTHER MATERIAL SUPPLIERS: Glass-fiber-reinforced-polymer reinforcement: Owens Corning, Concord, N.C., and New South Construction Supply, Greenville, S.C.; carbon-fiber-reinforced-polymer prestressing strand and spiral: Tokyo Rope USA, Canton, Mich.

traffic. Bridge No. 96 is functionally obsolete and required an emergency full-superstructure replacement in 2013 because the steel prestressing strands in the original cored-slab superstructure were extremely corroded.

NCDOT classifies this area of the state as highly corrosive due to the coastal marine environment. The standard corrosion-protection policy of the NCDOT Structures Management Unit for highly corrosive areas is to use concrete superstructures and substructures with increased concrete cover, epoxy-coated reinforcing steel, and concrete admixtures including calcium nitrite corrosion inhibitor, silica fume, and fly ash. During project development and planning, NCDOT recognized the need to provide a more durable concrete replacement structure that could withstand the harsh saltwater environment and provide greater resiliency than its predecessors.

Coinciding with the start of preliminary bridge design in 2017, NCDOT completed a state-sponsored research project with North Carolina State University to investigate the feasibility of using carbon-fiber-reinforced-polymer (CFRP) strands and glass-fiber-reinforced-polymer (GFRP) stirrups in prestressed concrete components. The research project greatly improved NCDOT's knowledge, experience, and acceptance of FRP reinforcing materials. NCDOT began looking for opportunities to use FRP materials as a corrosion protection measure. (See the Professor's Perspective article on page 54 of this issue of *ASPIRE*®.)

The 164-ft navigational span features five 78-in.-deep Florida I-beams with glass-fiber-reinforced-polymer stirrups and prestressed with carbon-fiber-reinforced-polymer strands. The span provides 125 ft of horizontal clearance and 45 ft of vertical clearance for vessel traffic. Photo: North Carolina Department of Transportation.

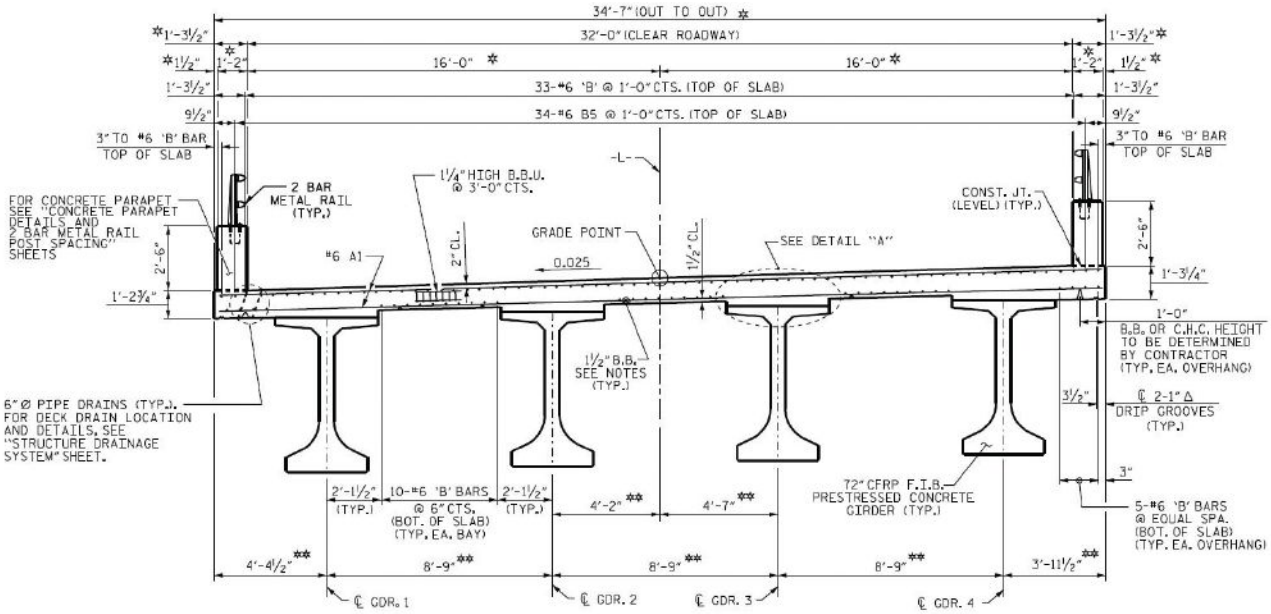
After internal meetings and discussions with various NCDOT technical units, including Construction, Materials & Tests, and Geotechnical Units, NCDOT leadership identified the Harkers Island bridge replacement as the project to implement the use of FRP reinforcing materials. They supported the effort to design the entire structure with FRP materials and, to the fullest extent possible, eliminate steel reinforcement. The size and scope of the structure were considered to be a benefit because the economies of scale would make the costs of the FRP reinforcing materials more competitive with those of traditional reinforcing materials. Additionally, NCDOT was awarded a $1 million Accelerated Innovation Deployment Demonstration grant from

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: 3200-ft-long bridge consisting of 28 spans of precast, prestressed concrete Florida I-beam (FIB) girders (span length up to 164 ft); the structure has a 45-ft vertical navigational clearance and an out-to-out width of 34 ft 7 in., with two 12-ft-wide lanes and 4-ft-wide shoulders

STRUCTURAL COMPONENTS: Fifty-six 54-in.-deep FIB girders (5580 linear ft total), forty-four 72-in.-deep FIB girders (5707 linear ft total), and fifteen 78-in.-deep FIB girders (1815 linear ft total), all with an 8¼-in.-thick cast-in-place sand lightweight concrete deck. Nineteen pile bents with cast-in-place bent caps and precast, prestressed concrete 24-in.-square piles, 10 three-column bents with cast-in-place concrete caps, and footings supported on precast, prestressed concrete 24-in.-square piles. All precast, prestressed concrete components are reinforced with carbon-fiber-reinforced-polymer (CFRP) strands and glass-fiber-reinforced-polymer (GFRP) bars; all cast-in-place concrete components are reinforced with GFRP reinforcement. End bents and roadway approaches are scour-protected by prestressed concrete sheet piles with steel prestressing strands.

BRIDGE CONSTRUCTION COST: $60 million ($540/ft^2)



The superstructure of the bridge has an out-to-out width of 34 ft 7 in., with two 12-ft-wide lanes and 4-ft-wide shoulders. The 8¼-in. cast-in-place sand lightweight concrete deck is reinforced with glass-fiber-reinforced-polymer bars and supported by prestressed concrete Florida I-beam girders. All Figures: North Carolina Department of Transportation.

the Federal Highway Administration to assist with offsetting FRP material costs. The size and scope of the project would also allow NCDOT and industry partners to better understand the opportunities and challenges associated with use of FRP materials that are often not realized when nontraditional materials and methods are used at a smaller scale. NCDOT anticipated a learning curve for all parties during design, fabrication, and construction, with the expectation that after the first precast concrete components were fabricated and substructure units placed, production processes would become more efficient.

Superstructure

The bridge superstructure has an out-to-out width of 34 ft 7 in., with two 12-ft-wide lanes and 4-ft-wide shoulders. The cast-in-place (CIP) sand lightweight concrete deck is 8¼ in. thick and reinforced with no. 6 GFRP bars. The deck is supported by precast concrete Florida I-beam (FIB) girders prestressed with CFRP strand. The GFRP-reinforced deck was designed in accordance with the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete*.[1] Sand lightweight concrete was used to reduce the dead load on the prestressed concrete girders and substructure, providing a more economical design by reducing both GFRP and CFRP material quantities, as well as substructure size. NCDOT's standard practice is to detail partial-depth prestressed concrete deck panels for corrosive sites. However, removable forms were specified for this project due to the use of sand lightweight concrete in the deck and the desire to avoid metal stay-in-place forms. For bridge expansion joints, foam joint seals with elastomeric concrete headers were located between the two- or three-span continuous units. Link slabs were used to minimize joints. The use of link slabs is advantageous for GFRP bars because it allows the use of straight bars exclusively. Detailing continuous-for-live-load diaphragms with bars having multiple bends would have been challenging to produce in GFRP reinforcement. The only steel reinforcement specified in the bridge superstructure or substructure is epoxy-coated reinforcing steel in the concrete parapet of the NCDOT standard two-bar metal rail. The two-bar metal rail is a common bridge rail used throughout North Carolina and is recognized for its aesthetics. NCDOT successfully crash tested the steel-reinforced bridge rail to the criteria specified in AASHTO's *Manual for Assessing Safety Hardware*[2] and decided against modifying the rail for GFRP reinforcing bars.

In multiple locations, the prestressed concrete Florida I-beam girders are supported by a cast-in-place bent cap on 24-in.-square prestressed concrete piles using carbon-fiber-reinforced-polymer strand and spiral. The average pile length for the project is 100 ft. Photo: North Carolina Department of Transportation.

The 8¼-in. sand lightweight concrete deck is reinforced with no. 6 glass-fiber-reinforced-polymer bars. Removable forms are used for deck construction. Photo: North Carolina Department of Transportation.

Production photo of a 100-ft-long, 54-in.-deep Florida I-beam precast concrete girder prestressed with forty-four 0.6-in.-diameter carbon-fiber-reinforced-polymer strands and reinforced with glass-fiber-reinforced-polymer stirrups. Photo: North Carolina Department of Transportation.

The CFRP prestressed concrete FIB girders were designed as simply supported for dead and live loads. Twenty-five of the 28 spans consist of a four-girder cross section using 54- or 72-in.-deep FIB girders with maximum span lengths of 100 or 130 ft, respectively. However, because the navigational span is 164 ft, an additional girder line and deeper girders were necessary to achieve a reasonable design using CFRP strands. As a result, the three spans around the navigational channel have a five-girder cross section with 78-in.-deep FIB girders.

Each 54-, 72-, and 78-in. FIB girder has forty-four, fifty-six, and sixty-four 0.6-in.-diameter CFRP prestressing strands, respectively. The 54-in.-deep girders had a 28-day design concrete compressive strength of 8 ksi and the 72- and 78-in.-deep girders were designed with 8.5-ksi concrete compressive strength. At the time of design, the manufacturer's guaranteed ultimate tensile strength for the CFRP prestressing strands was 339 ksi. The FIB girders use a typical NCDOT strand pattern with two strands in the 7-in.-wide web.

Contract plans provided design alternatives, giving the contractor the option to select either 0.63-in.-diameter CFRP or no. 5 GFRP stirrups for shear reinforcement. Contract provisions required the contractor to use the same stirrup material in all prestressed concrete girders. The higher strength and higher modulus of elasticity of the CFRP would enable the use of fewer stirrups in each girder, but the material cost per linear foot is less for GFRP than for CFRP. The alternatives were provided to encourage competitive material pricing and address potential supply chain challenges. The contractor elected to use GFRP stirrups for the project. A benefit of using the FIB girder shape is that many of the bar types and dimensions are interchangeable among the different girder sizes.

The CFRP prestressed concrete FIB girders were designed in accordance with the *AASHTO LRFD Bridge Design Specifications*,[3] the *AASHTO Guide Specifications for the Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems*,[4] the American Concrete Institute's *Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures* (ACI PRC-440),[5] and other technical reports. Engineers from state transportation agencies, including those from Florida, Michigan, and Virginia, provided valuable insights and collaboration throughout the design process.

The design of concrete girders prestressed with steel strand is generally controlled by service limit states (stresses), but for CFRP prestressed concrete girders the design was controlled in multiple instances by the strength limit state due to the 0.75 resistance factor that is applied for both compression and tension-controlled components. A design strand jacking force of $0.70f_{pu}$ (where f_{pu} is the design ultimate strength of the prestressing strand) was used for the CFRP prestressing strands.

The prestressed concrete girders are supported on steel-laminated elastomeric bearing pads with stainless steel sole plates and anchor bolts.

Substructure, Foundations, and Walls

The substructure of the bridge consists of pile bents and post-and-beam bents on pile-supported footings. The end bents and 17 of the interior bents are GFRP-reinforced CIP concrete bent caps on five or six 24-in.-square CFRP prestressed concrete piles. Ten interior bents are GFRP-reinforced CIP concrete bent caps on three columns with a footing supported by ten or fifteen 24-in.-square CFRP prestressed concrete piles. Substructure units were designed for vessel collision, which required battered piles. Owing to limitations with manufacturing larger-diameter bends in GFRP reinforcing bars, the main flexural reinforcement for the caps, columns, and footings are no. 8 bars. The members were designed using 90-ksi ultimate strength with a 0.7 environmental strength-reduction factor for the no. 8 GFRP bars. Stirrups, column spiral, and

Cast-in-place concrete footing is reinforced with glass-fiber-reinforced-polymer reinforcing bars. Not visible are the ten 24-in.-square precast concrete piles prestressed with carbon-fiber-reinforced-polymer strand. Photo: North Carolina Department of Transportation.

other miscellaneous reinforcing bars are predominately no. 5 GFRP bars. The CIP concrete substructure components were designed in accordance with the *AASHTO LRFD Bridge Design Specifications* and the *AASHTO Bridge Design Guide Specifications for GFRP-Reinforced Concrete*. The strength limit state required resistance factors of 0.55 for compression and tension-controlled components and 0.75 for shear.

One challenge of using GFRP material is providing adequate reinforcement to satisfy crack-control requirements. To avoid increasing the size of the substructure components and to provide a component that was easier to construct, NCDOT made exceptions to some of the crack-control requirements. Pile lengths for the 212 piles vary from 60 to 120 ft, with most of the piles being approximately 100 ft in length. The 24-in.-square CFRP prestressed concrete piles have sixteen 0.6-in.-diameter CFRP prestressing strands, 0.28-in.-diameter CFRP spiral, and 10-ksi design concrete strength.

Each end bent and approach roadway is protected from scour by a prestressed concrete sheet-pile wall. Prestressed concrete sheet-pile walls have a long history in North Carolina of providing durable, low-maintenance scour protection. The individual 2-ft 6-in.-wide by 1-ft-thick sheet piles range in length from 37 to 56 ft. Each sheet pile is prestressed with 22 conventional 0.6-in.-diameter, 270-ksi low-relaxation steel prestressing strands. Because the walls are not in constant contact with saltwater, the decision was made to use conventional steel strand and reinforcement in the sheet piles. Calcium nitrite corrosion inhibitor, silica fume, and fly ash were added to the concrete mixture to enhance durability and longevity of the sheet piles.

Project Construction

The project was let to construction in July 2021 and four bids were received. The winning contractor immediately started work because of a moratorium that prohibits any in-water work from April 1 through September 30 each year. By October 1, the contractor had commenced installing a temporary work bridge, and by November, crews were driving the first CFRP prestressed concrete test piles. The prestressed concrete piles and 54-in.-deep FIB girders were delivered to the jobsite by truck, and the 72- and 78-in.-deep FIB girders were delivered by barge.

There were initial construction challenges that involved revising

Installing formwork for cast-in-place concrete substructure columns reinforced with glass-fiber-reinforced-polymer reinforcing bars. Photo: Balfour Beatty.

Precast, prestressed concrete sheet-pile walls protect end bents and approach roadways from scour. Photo: North Carolina Department of Transportation.

GFRP bar details to accommodate manufacturing limitations. Extra splices were added to bent bars due to fabrication tolerances associated with bending GFRP. When the first CFRP prestressed concrete piles were field cut to the correct elevation, minor cracking occurred at the location of the CFRP strand. The cause of the cracking was attributed to the Hoyer effect of the CFRP strand, and the cracking in most instances was contained within the bent cap or footing. Later, it was noticed that the more time that elapsed between the pile casting and field cutting, the less likely it was that cracks would occur; eventually, no cracking was observed.

Collaboration among the contractor, precaster, FRP suppliers, and NCDOT contributed greatly to the success of the project. As of this writing, the project is nearing completion, with only a few spans of deck remaining to be placed, followed by barrier rail installation. The contractor is scheduled to have the bridge ready for traffic by the end of 2023, which will be 10 months ahead of the contract schedule.

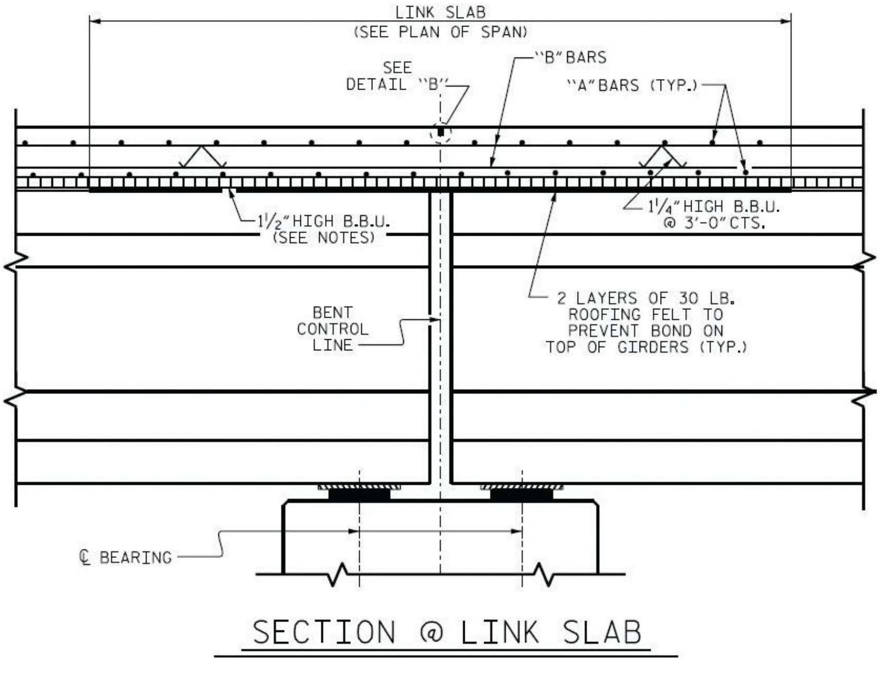
The Harkers Island bridge replacement project is a monumental project for NCDOT. The lessons learned throughout the design and construction of this project are already being applied to other active NCDOT projects using CFRP and GFRP reinforcement. The project has accelerated the adoption of FRP materials by NCDOT and promotes new business practices that will provide longer-lasting structures with improved durability and greater resiliency in North Carolina's corrosive coastal environments.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2018. *AASHTO LFRD Bridge Design Guide Specifications for GFRP-Reinforced Concrete.* 2nd edition. Washington, DC: AASHTO.
2. AASHTO. 2016. *Manual for Assessing Safety Hardware.* 2nd ed. Washington, DC: AASHTO.
3. AASHTO. 2017. *AASHTO LRFD Bridge Design Specifications*. 8th ed. Washington, DC: AASHTO.
4. AASHTO. 2018. *AASHTO Guide Specification for the Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems*. Washington, DC: AASHTO.
5. American Concrete Institute (ACI). 2007. *Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures*. ACI PRC-440-07. Farmington Hills, MI: ACI.

Trey Carroll is an assistant state structures engineer and Ashvin Patel and Ahmad Ighwair are bridge engineers in the Structures Management Unit of the North Carolina Department of Transportation in Raleigh.

Link slabs were used to minimize joints and avoid detailing continuous-for-live-load diaphragms with bars having multiple bends, which would have been challenging to produce using glass-fiber-reinforced-polymer (GFRP) reinforcement. The use of link slabs is advantageous for GFRP bars because it allows the use of straight bars.



CONCRETE BRIDGE STEWARDSHIP

Joining Forces

Concrete and steel bridge champions collaborate to develop thorough life-cycle assessments and lower embodied-carbon material procurement requirements for bridges

by John Cross and Emily Lorenz

On the surface, two recent federal initiatives—one to increase infrastructure spending and the other to reduce carbon emissions—seem mutually exclusive, which raises the question of whether more bridges can be built while simultaneously lowering the carbon emissions associated with their construction. The answer is that these two objectives can coexist, but only if a consistent and robust technical framework is in place for evaluating the embodied-carbon impacts of the materials used in bridge construction.

To address this challenge, the steel and concrete industries have joined together to develop fair and technically robust life-cycle assessment (LCA) requirements for the bridge market. The National Concrete Bridge Council (NCBC) and the National Steel Bridge Alliance (NSBA) are working together to craft a guidance document for properly conducting an LCA that is specifically applicable to bridges. The guidance will also address the procurement of materials with less embodied carbon.

The guidance document will be especially valuable to state departments of transportation (DOTs) that are increasing their infrastructure investments but must adhere to laws and regulations designed to reduce the embodied-carbon impact of construction materials.

The following are among the recent federal, state, and local initiatives that are driving this push toward more-sustainable solutions:

- The Federal Highway Administration issued a vision for pavements: "To advance the knowledge and practice of designing, constructing, and maintaining more-sustainable pavements through stakeholder engagement, education, and development of guidance and tools."[1]
- The White House has set economy-wide greenhouse gas emission targets: 50% reduction by 2030 and 100% reduction by 2050 (based on 2005 baseline).[2]
- A federal Buy Clean initiative was announced in September 2022.[3]
- A carbon-reduction program was created through the Infrastructure Investment and Jobs Act of 2021.[4]
- California, New York, Colorado, Minnesota, and Oregon are among the states to enact Buy Clean laws that establish embodied-carbon thresholds for purchasing construction materials for buildings and infrastructure projects.[5]

These initiatives can only be successful if the embodied-carbon impacts they seek to reduce can be accurately and consistently measured and quantified.

Design decisions need to be based on numerous analytical factors, including the environmental impacts of alternative scenarios. Today, properly evaluating the embodied-carbon impacts of a project in terms of its global warming potential (GWP) is critical. A bridge LCA is a necessary component of measuring GWP and must be based on a consistent and sound technical methodology.

But the effort to reduce embodied carbon must not end there. Identical products from different producers will have different embodied-carbon impacts associated with differences in the producers' manufacturing and production processes. Procurement guidelines are necessary to ensure that any differences in manufacturing processes from company to company do not impede the production of low-embodied-carbon products.

Today's bridge market lacks comprehensive tools to quantify and reduce negative environmental impacts. The first step in developing the tools is the LCA guidance document.

Why a Consistent LCA Framework Is Needed

Current Buy Clean laws and embodied-carbon-reduction specifications for steel and concrete materials used in bridges are technically insufficient and were developed without industry input. Laws, reguations, and specifications sometimes disagree with ISO standard requirements that have established the methods for measuring, evaluating, and reporting environmental impacts. Without technically accurate requirements, DOTs cannot know if they are truly accomplishing the mandated goal of reducing the environmental impact of concrete and steel bridges.

What Will Be Developed

The steel and concrete industries have been conducting LCAs for more than 20 years and have the longest history of evaluating and reporting the environmental impacts associated with structural materials. Representatives of these industries are well versed in the ISO standards that are used during assessments, and they frequently serve on the committees that develop these standards. The joint effort of the steel and concrete industries will provide the best opportunity for crafting technically sound language that can be used to accurately determine real reductions in environmental impacts, including embodied carbon. By joining together to develop resources, the concrete and steel bridge industries can ensure that the requirements that will be implemented are equitable and technically correct.

The steel-concrete collaboration aims to develop a guidance document on how to properly conduct LCAs for bridge projects and address the procurement of materials. This guidance document will:

- maintain technical accuracy and adherence to ISO standards;
- emphasize the importance of performance in conjunction with reducing environmental impacts;
- frame decision-making from a whole-life-cycle context and evaluate a full set of environmental impacts;
- be mindful of existing DOT requirements and the Envision rating system (a system similar to LEED but for infrastructure projects) to harmonize with current industry practices, where possible;
- solicit feedback from bridge engineers, DOTs, and other agencies during work-product development.

It is anticipated that draft guidelines will be available for review in mid-2024.

Gregg Freeby, chair of NCBC, states, "NCBC looks forward to the collective efforts between the concrete and steel industry groups on a scientific-based approach to aid bridge practitioners in assessing and reducing the embodied carbon in the design and execution of their projects."

Chris Garrell, NSBA chief bridge engineer, states, "NSBA is thrilled to work on this collaborative effort to standardize the environmental assessment of steel and concrete bridges, and we're confident that the marketplace will benefit from this unified approach."

References

1. Ram, P. V., J. T. Harvey, S. T. Muench, et al. 2017. *Sustainable Pavements Program Road Map*. FHWA-HIF-17-029. Washington, DC: Federal Highway Administration (FHWA). https://www.fhwa.dot.gov/pavement/sustainability/hif17029.pdf.
2. The White House. n.d. "National Climate Task Force." Accessed August 30, 2023. https://www.whitehouse.gov/climate.
3. The White House. 2022. "Fact Sheet: Biden-Harris Administration Announces New Buy Clean Actions to Ensure American Manufacturing Leads in the 21st Century." https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/15/fact-sheet-biden-harris-administration-announces-new-buy-clean-actions-to-ensure-american-manufacturing-leads-in-the-21st-century/.
4. FHWA. 2023. "Fact Sheets: Carbon Reduction Program (CRP)." https://www.fhwa.dot.gov/bipartisan-infrastructure-law/crp_fact_sheet.cfm.
5. Carbon Leadership Forum. 2022. "Implementing Buy Clean." https://carbonleadershipforum.org/implementing-buy-clean/.

EDITOR'S NOTE

It is unusual for organizations representing competing materials to join forces. However, the consequences of allowing other parties—unfamiliar with the materials, processes, and existing requirements, or lacking the technical background—to create LCA requirements for the bridge industry would have long-term adverse effects for all, including the general public. NCBC and NSBA are knocking down the traditional barrier to join in the development of guidance, based on science, on properly conducting whole-life-cycle assessments for bridge projects. Look to ASPIRE® for future updates on the progress of this historic effort.

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Why Use Precast, Prestressed Concrete Piles?

by Roy L. Eriksson, Eriksson Technologies Inc.

There is a widely held misconception that driven precast, prestressed concrete piles (PCPs) are principally for use in marine and river structures. As a result of this unfortunate misconception, PCPs are often prematurely eliminated from consideration during the preliminary design phase of other projects. The truth is, however, that PCPs are a high-performance, durable, and cost-effective solution that are typically a great choice for many deep foundation projects. Yes, they are certainly an excellent choice for marine and other in-water applications, but PCPs have many qualities that make them suitable for nearly all foundation types, including on-land structures.

Another misconception is that PCPs cannot be used in moderate- or high-seismic areas. However, PCPs can be easily designed and detailed to provide the ductility required by code or by agency specifications to resist seismic loads.

Precast concrete as a material provides many benefits for structural components. Furthermore, compared with piles made from other materials, PCPs gain the following additional advantages:

- *Adaptability:* From small-diameter piles on land to 200-ft-long single-piece marine piles in saltwater, PCPs have a wide range of sizes and cross-sectional shapes. PCPs can also be spliced for deeper depths.
- *Sustainability:* Local materials and labor, long service life, reusable formwork, and reduced amounts of concrete and material waste enhance

Precast, prestressed concrete piles are cast in steel forms in long-line casting beds under factory-controlled conditions. Pile dimensions and material properties are tightly controlled. Photo: Gulf Coast Pre-Stress Partners Ltd.

The main type of reinforcement in precast, prestressed concrete piles is high-strength prestressing strands. During casting, the strands are anchored against thick steel plates that facilitate precise placement of the individual strands. Photo: Roy L. Eriksson.


Once a precast concrete pile has been cast and removed from its form, it is fully prestressed and can be easily and safely lifted, handled, and transported to the jobsite. Note that at this stage, the entire pile can be fully inspected. Photo: Roy L. Eriksson.

the sustainability of PCPs. Sustainability can be further improved with high-performance concrete, which can significantly reduce the cross-sectional areas of components, resulting in less material being required.

- *Quality control:* The quality of PCPs is facilitated by nationally recognized quality-assurance and quality-control procedures. Also, the ability to visibly inspect finished PCPs before installation helps ensure high-quality outcomes.
- *Structural efficiency:* High-strength concrete and prestressing allow for smaller cross sections. PCPs have greater capacities than steel H-piles, which means fewer piles are needed and smaller footprints can be achieved. Longitudinal and confinement reinforcement run the full length of the PCP, providing high flexural strength and enhanced ductility from end to end. Due to cross-sectional symmetry, high lateral stiffness is provided in all directions in PCPs, unlike steel H-piles.
- *Long design life:* The use of high-performance concrete with low permeability, combined with permanent axial compressive stress that provides excellent crack control, results in low moisture intrusion, low corrosion, and excellent durability.
- *Accelerated construction:* PCPs are fabricated off site at a plant and prior to or concurrent with jobsite activities, which greatly accelerates construction schedules.
- *No drilling spoils:* PCPs are displacement piles, so the need to dispose of drilling spoils is eliminated. That gives PCPs a distinct advantage over drilled-in piles and shafts on sites that might have subsurface contamination.
- *Densification of surrounding soil:* As piles are driven into granular soils, the soil surrounding the piles is densified, which increases skin friction and end-bearing capacities. Solid PCPs displace larger volumes than thin-walled sections, such as steel H-shapes, which causes further densification.
- *Bearing capacity*: Testing to verify bearing capacity is often not needed with PCPs. Pile driving analyzer tools may be used to verify pile capacities. Pile-driving contractors say it best: "A driven pile is a tested pile."

Available precast, prestressed concrete pile shapes and sizes vary by region and by manufacturer, but the most common shapes in the United States are square, octagonal, or round (cylindrical) in cross section. Typical sizes range from 10-in.-square solid piles to 66-in.-diameter hollow cylinder piles.

PCPs are an engineered product, made of precast, prestressed concrete. Concrete alone can resist very high compressive stresses, but relatively low tensile stresses. Typical reinforced concrete overcomes this by incorporating reinforcing bars to carry the tensile stress. Prestressed concrete takes this concept to a much higher level by replacing the typical Grade 60 (60-ksi yield strength) reinforcing bars with high-strength (270-ksi ultimate strength) prestressing strands. Before casting, each strand is tensioned to about 70% of its ultimate strength and then anchored at the ends of the stressing bed. Once the transverse reinforcement (ties or spiral) has been placed in the casting form and the concrete has been placed and cured, the prestressing strands are detensioned and the prestressing force transfers to the concrete pile. This precompresses the pile

A typical on-land pile-driving operation allows piles to be stockpiled on site for easy access. Precast, prestressed concrete piles are displacement piles that create no spoil at the site. Photo: Concrete Technology Corp.

Prestressed concrete piles are typically square, octagonal, or round (cylindrical). Availability of shapes and cross sections varies by geographical region. Photo: PCI.

with a uniform level of axial compression, which enables the pile to resist much higher levels of tension from applied loads whether they be from driving or in service.

Prestressing a concrete pile produces several benefits. Principal among them is the ability to mitigate cracking of the concrete. The integrity of the pile is preserved and protected during its entire service life, from stressing bed to handling and hauling, pile driving, incorporation into a structure, and in-service loading. With prestressing, corrosion is effectively mitigated, which greatly improves durability. An uncracked section also means the stiffness of the pile is maintained under flexural loading.

PCPs are typically fabricated using steel forms on long-line casting beds in permanent facilities with proven quality-control and quality-assurance procedures. Because the cross-sectional dimensions are defined by the form, the shape of the pile remains true and constant along the entire length of the pile form. The prestressing strands are anchored at each end of the bed against thick steel plates through which the strands pass. These plates are predrilled with a fixed hole pattern that defines the location of each strand. Therefore, concrete cover—the clear distance between the edge of a strand and the face of the pile—remains constant, as required by design code or specifications. As a result, corrosion resistance is not compromised by insufficient concrete cover, greatly enhancing pile durability.

Durability is also enhanced by virtue of the concrete being mixed in the precast concrete plant, which gives greater control over the concrete mixture proportions and consistency among batches. Admixtures of various types can easily be blended into the concrete mixture. Water-reducing admixtures can be added to improve concrete flowability and workability. Additives such as calcium nitrate inhibitor, which improves corrosion resistance, can also be added.

Continuous improvements to existing materials and the introduction of new materials have increased the performance of precast, prestressed concrete. New prestressing strand types include larger-diameter strand, higher-strength steel, stainless steel strand, and carbon-fiber-reinforced-polymer strand. Performance-enhancing additives include structural fiber that can be blended into the concrete mixture. Advances in the science of materials have resulted in a new class of concrete called ultra-high-performance concrete (UHPC), which is typically defined as having a compressive strength of at least 17 ksi, a defined flexural strength, and enhanced tensile strength. As a result, new pile shapes are being developed that start to approach the shape of steel H-piles.

So, why use precast, prestressed concrete piles for your next project? The real question is: *why not?*

Additional Resources

The following publications offer more detailed information about precast, prestressed concrete piles as well as design resources:

- White, C. D., R. W. Castrodale, and M. C. Nigels. 2004. *Precast Prestressed Concrete Piles*. BM-20-04 (*Bridge Design Manual* Chapter 20). Chicago, IL: Precast/Prestressed Concrete Institute (PCI).
- PCI Prestressed Concrete Piling Committee. 2019. "Recommended Practice for Design, Manufacture, and Installation of Prestressed Concrete Piling." *PCI Journal* 64 (4): 84–116. https://doi.org/10.15554/pcij64.4-05.
- Parkins, J., D. Eckenrode, and R. Eriksson. 2021. "Precast, Prestressed Concrete Piles." PCI webinar, December 14, 2021.

EDITOR'S NOTE

In addition to the resources noted in the article, other tools, webinars, and related articles can be accessed through the PCI website. Included are two new PCI eLearning modules—T624: **Overview of PCI's Recommended Practice for Prestressed Concrete Piles** ***and T626:*** **Application of PCI's Recommended Practice to Building Piles*****—which are now available at https://www.pci.org/HowPrecastBuilds/Component/Piles.aspx.***

CONCRETE BRIDGE TECHNOLOGY

Cross-Section Efficiency: It's Not Just for Superstructures

by John M. Holt, Modjeski and Masters Inc., Christopher White, Volkert Inc., and Jorge Hinojosa, Bexar Concrete Works

Precast, prestressed concrete beams and girders are common superstructure elements for tens of thousands of bridges in the United States. The cross sections of the most common beam and girder shapes (I, bulb tee, stemmed, and box) were developed with cross-sectional efficiency as a goal. Numerous engineers, going back to the prominent French bridge engineer Yves Guyon in the early 1950s, have proposed equations or methods to evaluate and compare the cross-sectional efficiency of various precast, prestressed concrete girders.[1] These methods all seek to provide structurally efficient cross sections that maximize flexural capacity while minimizing girder area and weight.

However, minimizing girder area is not the only consideration in developing structurally efficient precast, prestressed concrete sections. With precast, prestressed concrete girders, if engineers focus solely on optimizing flexural cross-sectional efficiency, the result may be a girder section lacking structural capability in other areas and that may be challenging in terms of fabrication and handling. For example, a highly efficient precast concrete girder section may have very thin webs and wide, thin top and bottom flanges (similar to a steel I-girder). Such cross sections could have bottom flanges that are not large enough to contain the prestressing strands required to make the section structurally capable relative to its depth. Or the flanges may be so wide and thin that achieving consistent concrete quality is challenging in the flange extremities, which also poses challenges for handling and transportation. The web may be so thin that proper consolidation of the concrete during placement is difficult and shear strength is compromised in favor of flexure.

Most transportation agencies have their own standardized precast, prestressed concrete girder cross sections that were developed taking multiple factors into consideration, and without sacrificing cross sectional efficiency. Standardization of cross sections greatly improves the cost-effectiveness of precast, prestressed concrete girder superstructures by enabling fabricators to invest in durable, reusable forms at a relatively low capital cost per use.

Substructure Cap Beams

Currently, more substructure cap beams are being constructed using precast or precast, prestressed concrete for many of the same reasons that make precast, prestressed concrete superstructure girders so effective: ease of fabrication, speed of construction, serviceability, and economy. Substructure cap beams can be used to reduce the proximity and duration of lane closures, traffic shifts, and equipment operation in construction work zones. Therefore, they can be an effective tool for accelerated bridge construction and optimizing worker and roadway-user safety.

However, because precast concrete substructure options are often a "one-off" solution for a particular project, many cap-beam cross sections are designed without adequate consideration of structural efficiency. Instead, they are often designed to use solid, uniform-width cross sections to conform with paradigms of typical cast-in-place construction practice, or the design vision is limited to precast concrete solutions used on previous projects with different constraints or purposes.

A Tale of Two Caps

An example comparing two bridge straddle cap beams, both 12 ft wide and 12 ft deep, highlights the differences between a solid, uniform-width cross section and a more efficient hollow cross section (**Fig. 1**). This simple comparison assumes that each post-tensioning tendon in the sections has an effective prestress of 1300 kip. The span length of each cap is 125 ft.

Table 1 lists the cap section properties and the effects of prestressing on the caps. The solid cap has a maximum unfactored self-weight moment of approximately 42,188 kip-ft, whereas the hollow, structurally efficient cap has a maximum self-weight moment of 15,820 kip-ft. To provide a Service I moment of approximately 47,000 kip-ft, which corresponds to acceptable stresses, 10

Figure 1. A schematic of the solid and hollow cap-beam cross sections used in the example calculation to demonstrate the design differences between the two sections. With the same design criteria, the solid section requires 10 post-tensioning tendons, whereas the hollow section requires 6 post-tensioning tendons. Figure: Modjeski and Masters.

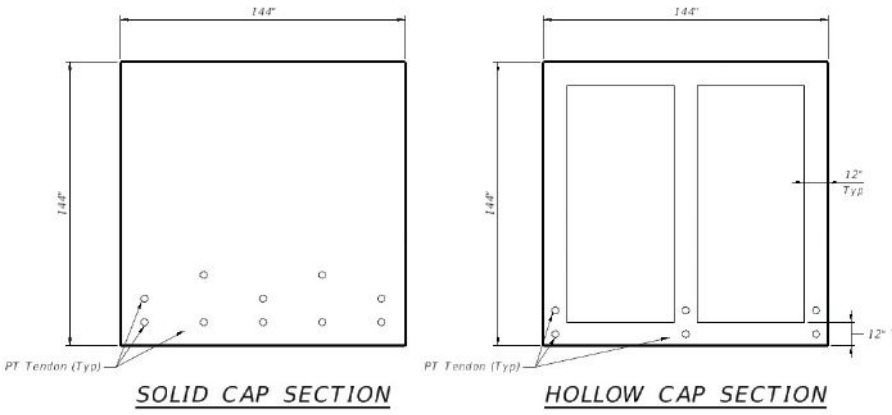


Table 1. Comparison of straddle cap sections

	Solid section	Two-cell section
Cap span length, ft	125	125
Cap area, in.^{2}	20,736	7,776
Cap self-weight, kip/ft	21.6	8.1
Cap moment of inertia *I*, in.^{4}	35,831,808	5,225,472
Cap section modulus *S*, in.^{3}	497,664	281,664
Cap self-weight moment, kip-ft	42,188	15,820
Number of tendons, row 1	5	3
Row 1 eccentricity, in.	64	64
Number of tendons, row 2	3	3
Row 2 eccentricity, in.	56	56
Number of tendons, row 3	2	0
Row 3 eccentricity, in.	48	—
Effective prestress, kips per tendon	1300	1300
Service I moment required to provide acceptable stresses, kip-ft	47,079	46,724

Table: Modjeski and Masters.

tendons consisting of thirty-seven 0.6-in.-diameter strands each are needed for the solid cap, whereas only 6 tendons are needed for the hollow cap. A large percentage of the prestressing is needed just to overcome the additional weight of the solid cap.

While the solid cap may be slightly easier to construct than the hollow cap, it may require special measures to mitigate mass concrete placement issues. If precasting is an option, the lower weight for lifting and transportation of the hollow cap is clearly advantageous.

Strategies for Efficient Cap Beams

Hollow sections are one of the first considerations for developing a structurally efficient substructure cap beam. A closed, hollow section is an excellent selection, especially when torsion is present. Not all interior voids need to be rectangular in shape. They could be circular or other shapes, depending on the method of forming, whether using removable plywood forms or foam that is cut to shape and left in place. Another attractive aspect of hollow caps is the ability to vary the cap beam's web thickness internally to assist with shear demands without altering the outward appearance of the cap.

If torsional resistance isn't a primary issue, open shapes such as a T-section or an inverted U-section may be attractive choices to achieve structural efficiency. If the cap is to be precast concrete, a T-section may be a better choice than an inverted U-section because no internal formwork is needed. **Figure 2** shows an example of a variable-depth T-section used for a precast, prestressed concrete hammerhead pier cap.

Conclusion

To take full advantage of the benefits of prestressing and/or precasting substructure cap beams, designers need to adopt the principle of cross-sectional efficiency in their designs, rather than proportioning cap cross sections using the past practices and constraints of traditional cast-in-place concrete construction. Such efficiency principles have been successfully applied on several projects in Texas, such as three bridges on Loop 1604 in San Antonio, U.S. Route 183 in Austin, the Interstate 2/Interstate 69 design-build project in Hidalgo County, and the Gulf Intercoastal Waterway Bridge at Sargent Beach in Matagorda County (see the Project article in the Winter 2022 issue of *ASPIRE*® for more information).

Reference

1. Rabbat, B. G., and H. G. Russell. 1982. "Optimized Sections for Precast Prestressed Bridge Girders." *PCI Journal* 27 (4): 88–108. https://doi.org/10.15554/pcij.07011982.88.106.

John M. Holt is a senior technical advisor for Modjeski and Masters Inc. in Round Rock, Tex. Christopher White is a senior technical advisor for structures for Volkert Inc. in Houston, Tex. Jorge Hinojosa is a general manager for Bexar Concrete Works in San Antonio, Tex.

Figure 2. Variable-depth T-shaped precast, prestressed concrete hammerhead pier cap. Photo: Bexar Concrete Works.

CONCRETE BRIDGE TECHNOLOGY

Flexural Design Considerations for Prestressed Concrete Girders Using Stainless Steel Strands

by Dr. Anwer Al-Kaimakchi, Corven Engineering, an H&H company, and Dr. Michelle Rambo-Roddenberry, FAMU-FSU College of Engineering

Several articles by Dr. Oguzhan Bayrak in previous issues of *ASPIRE*® have addressed topics of structural behavior and redundancy. In the article published in the Winter 2021 issue, Bayrak discussed the considerations that should be made to incorporate new materials into design specifications and how those new materials may affect the behavior of members. New materials may require the engineer to adapt to a new philosophical approach to design. This is the case when prestressed concrete members are designed with stainless steel prestressing strand. Stainless steel strand is an emerging type of strand that is desirable in concrete members in extremely aggressive environments because it is highly resistant to corrosion. This property leads to a longer service life, lower maintenance costs, and fewer disruptions to the public. Unlike conventional carbon steel strand, stainless steel strand is not at risk for rust from environmental exposure while stored at the casting yard. Although the corrosion resistance of stainless steel strand is superior to that of carbon steel strand, the tensile strength, total elongation, and modulus of elasticity of stainless steel strand are lower, which influences the flexural behavior of members. In December 2020, a report was published for a Florida Department of Transportation (FDOT)–sponsored research project that investigated the use of 0.6-in.-diameter stainless steel strands in prestressed concrete I-girders.[1] This article discusses selected key findings from the project, special behavior of stainless steel strand, and important design considerations when designing with stainless steel strand.

Mechanical Properties

The mechanical properties of the strands are a key factor in the flexural behavior of a prestressed concrete girder. Stainless steel strand is relatively new to the construction industry. ASTM A1114, *Standard Specification for Low-Relaxation, Seven-Wire, Grade 240 [1655], Stainless Steel Strand for Prestressed Concrete*,[2] was published in April 2020. **Table 1** shows guaranteed mechanical properties of 0.62-in.-diameter stainless steel and carbon steel strands specified in ASTM A1114[2] and ASTM A416,[3] respectively. The guaranteed tensile strength of stainless steel strand is 88.9% of that of carbon steel strand, and the guaranteed tensile strain of stainless steel strand is 0.014, which is only 40% of the value for carbon steel strand. These values are evident in **Fig. 1**, which superimposes a typical stress-strain curve for carbon steel strand onto a stress-strain curve of stainless steel strand based on experimental tests of specimens from two spools of strand by Al-Kaimakchi and Rambo-Roddenberry.[4] Also, tensile tests revealed that the elastic modulus of stainless steel strand from the two spools was between 23,900 and 25,800 ksi; by comparison, the nominal elastic modulus for carbon steel strand is 28,500 ksi.

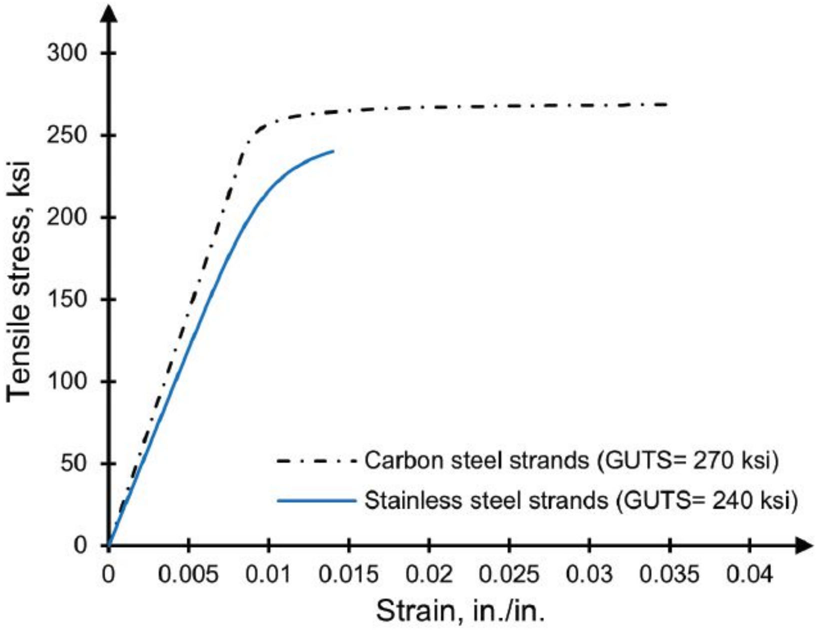
Experimental Behavior of Girders with Stainless Steel Strands

A prestressed concrete girder can fail in flexure by either crushing of concrete in the compression zone or rupture of strands in the tension zone. Because of the low ultimate strain (total elongation) of stainless steel strand (Fig. 1 and Table 1), some girder designs are expected to fail due to rupture of the strands before the concrete in the compression zone reaches its ultimate strain. This expectation is contrary to the design philosophy for girders with carbon steel strands where the girders are designed to fail due to crushing of concrete after yielding of the strands.

Full-scale flexural tests on five 42-ft-long AASHTO Type II girders (design concrete compressive strength of 8.5 ksi), all with an 8-in.-thick, 24-in.-wide composite concrete deck slab (design concrete compressive strength of 4.5 ksi) and prestressed with stainless steel strands, were conducted for FDOT. The number of strands (reinforcement ratio) was the only design variable.[1] Each strand was tensioned at the casting yard to an initial force of 36 kip, which was 65% of the guaranteed ultimate tensile strength. As anticipated, the girders

Table 1. Specified minimum mechanical properties of 0.62-in.-diameter strands

Mechanical properties	Stainless steel strand	Carbon steel strand
	ASTM A1114[2]	ASTM A416[3]
Diameter, in.	0.62	0.62
Area, in.^2	0.231	0.231
Yield strength, lbf	49,860	56,520
Breaking strength, lbf	55,400	62,800
Total elongation	1.4%	3.5%



Note: GUTS = guaranteed ultimate tensile strength.

Figure 1. Comparison of stress-strain curves of stainless steel and carbon steel strands. All Figures: Anwer Al-Kaimakchi.

failed due to rupture of strands while the concrete compression zone was still intact (**Fig. 2**). Experimental results showed that girders with larger numbers of stainless steel strands:

- exhibited larger deflections and ultimate loads at failure,
- had higher concrete top-fiber strains at failure, and
- had more flexural cracks and smaller crack spacings.

Before failure, the girders exhibited noticeable deflection and widespread cracking, both of which are desirable before failure.

Parametric Study of Behavior of Girders with Stainless Steel Strands

From the results of a parametric study (using 7 to 21 strands) conducted with the same composite girder cross section that had been used for the FDOT research project, Al-Kaimakchi and Rambo-Roddenberry determined relationships between the number of stainless steel strands (reinforcement ratio), flexural resistance, ultimate curvature, and ultimate deflection for concrete I-girders (**Fig. 3**).[4] The left part of Fig. 3 shows that the factored flexural resistance (ϕM_n) of the girder increases with an increase in the number of stainless steel strands. A balanced failure (simultaneous crushing of concrete and rupture of the stainless steel strands) occurs at the number of strands represented by the red triangle. Extending a solid horizontal red line to the other graphs, the designs above the solid red line fail by crushing of concrete (compression controlled) and designs below the red line fail by rupture of the stainless steel strands (tension controlled).

Figure 2. In a research study conducted for Florida Department of Transportation, 42-ft-long AASHTO Type II girders, all with 8-in.-thick, 24-in.-wide composite deck slabs and prestressed with stainless steel strands, were tested in flexure.[1] This photo shows a girder with nine strands immediately after failure by strand rupture. Girders with seven and eleven strands failed in the same manner.

Figure 3 (middle and right) shows that when a girder is expected to fail due to rupture of strands (below the red line), ultimate curvature and deflection increase as the number of stainless steel strands increases. Based on the relationship in **Eq. (1)**, the concrete top-fiber strain at failure ε_c also increases as the number of strands increases. Continuing to increase the number of stainless steel strands will eventually result in simultaneous failure (red triangle) of both concrete in the compression zone and the stainless steel prestressing strands in the tension zone. As mentioned previously, increasing the number of strands beyond the balanced failure point results in failure by crushing of the concrete. When the girder is expected to fail due to crushing of concrete, ultimate curvature and ultimate deflection decrease with an increase in the number of stainless steel strands because the net tensile strain decreases (Eq. [1]).

Ultimate curvature (curvature at failure):

$$\phi = \frac{\varepsilon_c}{c} = \frac{NTS}{d-c} \qquad (1)$$

where

ε_c = concrete top-fiber strain at failure
c = depth of neutral axis
NTS = net tensile strain in the bottom row of strands
d = distance from the top fiber to the bottom row of strands

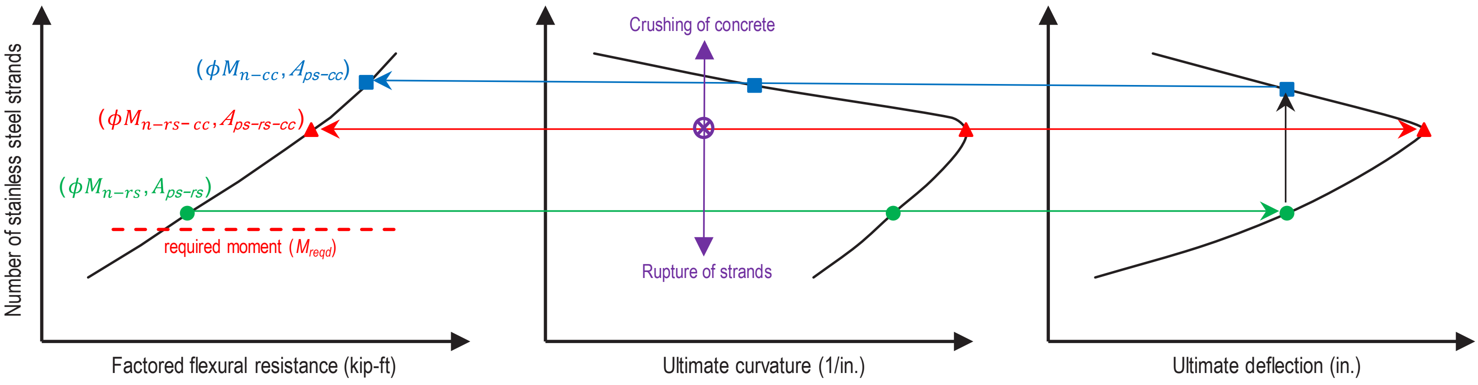


Figure 3. Behavior of a prestressed concrete girder with stainless steel strands: flexure (left), curvature (middle), and deformation (right).

It is significant to note that for all of the designs represented in Fig. 3, *NTS* is greater than 0.005, which is the lower limit of net tensile strength for which sections can be considered to be tension-controlled in the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[5] That means all the designs in this figure are within the requirements for tension-controlled behavior, even though the failure mode (concrete crushing or strand rupture) is generally considered to be nonductile.

Optimal Design

One goal in the design of a prestressed concrete member is to determine the number of stainless steel strands required to satisfy the requirements of the AASHTO LRFD specifications. For the purpose of this discussion, let us assume the design moment required by the AASHTO LRFD specifications that controls the design of a bridge is M_{reqd}, which is shown in Fig. 3 (left) as a dashed red line. The required design moment could be defined by the Strength I limit state, minimum reinforcement provisions, or the Service III limit state. The factored flexural resistance ϕM_n must be greater than or equal to M_{reqd}; therefore, any number of strands above the dashed red line satisfies the minimum requirements of the AASHTO LRFD specifications. For a factored flexural resistance ϕM_{n-rs} (shown as solid green circle in Fig. 3), which is slightly greater than M_{reqd}, the number of stainless steel strands is A_{ps-rs}. For this number of strands, the failure mode is rupture of strands. The corresponding ultimate curvature and ultimate deflection (that is the curvature and deflection, respectively, at failure) for A_{ps-rs} are shown in Fig. 3 (middle) and Fig. 3 (left), respectively. By increasing the number of strands to A_{ps-cc} as indicated by the solid blue square in Fig. 3, the failure mode changes from rupture of strand to crushing of concrete (Fig. 3 [middle]), while achieving the same ultimate deflection (Fig. 3 [right]).

Although designing for the crushing of concrete failure mode leads to greater flexural resistance of the girder, it does not result in the greatest ultimate deformation. Figure 3 shows that the greatest ultimate curvature and deflection (red triangle) is achieved when the girder fails due to simultaneous failure of concrete crushing in the compression zone and strand rupture in the tension zone. Depending on the value of the required moment M_{reqd}, increasing the number of strands only to achieve failure by crushing of concrete might not be necessary. Also, a different parametric study has shown that failure by concrete crushing may not be achievable for I-girders with a wide composite deck slab (large beam spacing).[1]

The region in Fig. 3 between the green circle and red triangle may be the desirable design area for bridge engineers, although designs in this zone lead to failure by rupture of strands. While strand rupture has not been seen as a desirable failure mode in the past, experimental results from the FDOT research project show that girders failing due to rupture of strands can still exhibit noticeable deformation and cracking before failure (Fig. 2), and can have significant reserve strength between the first flexural cracking and failure.[1] For optimal design in terms of deformability, area of stainless steel prestressing strand must be closer to $A_{ps-rs-cc}$ (the red triangle in Fig. 3).

Designing for Deformability

It is important that a structural member exhibit adequate deformation and cracking to give warning before failure. A common concern regarding the use of stainless steel strands is their low ultimate strain and the resulting limited expected deformation of the girder before failure.

There are two ways to increase the amount of deformation before failure of a girder prestressed with stainless steel strands that is anticipated to fail by rupture of strands.

- Increase the number of strands (reinforcement ratio). That results in an increase in concrete top-fiber strain ε_c, thereby increasing the curvature (Eq. [1]) and deflection at failure. This was demonstrated experimentally[4] and can also be seen in Fig. 3. For areas of stainless steel prestressing strand less than $A_{ps-rs-cs}$, increasing the number of strands results in an increase in ultimate deflection (Fig. 3 [right]). The question is, what would be the most appropriate target value for the concrete top-fiber strain when rupture of strand is the expected failure mode? For the greatest deformation, and therefore warning before strand rupture, the answer is the higher, the better: closer to 0.003 in./in.
- Decrease the initial tensioning stress in the strands (unless the design is controlled by the Service III limit state). The initial tensioning level affects the net tensile strain in the strands at failure. A greater net tensile strain (lower initial tensioning level) is desirable to achieve greater curvature at failure. Thus, ultimate curvature can be increased by increasing the net tensile strain as a result of reducing the initial tensioning stress (Eq. [1]).

This approach is contrary to the philosophy for designing with carbon steel strands, where the designer typically uses the maximum permitted initial tensioning level of the strand to satisfy concrete stress limits at the service limit state with the fewest strands. Engineers designing with stainless steel strands will need to have a deeper understanding of the material properties and be aware of strategies to deal with the consequences of the limited ultimate strain.

Conclusion

This article discusses the philosophy for designing precast concrete girders prestressed with stainless steel strands. Stainless steel strand has a much lower ultimate strain than conventional carbon steel strand, and this difference in material behavior has a significant effect on girder behavior. However, full-scale experimental tests have shown that precast concrete girders prestressed with stainless steel strands that fail due to rupture of strands may still have significant reserve strength from first flexural cracking to failure and exhibit noticeable cracking and deflection well before reaching their ultimate capacity. Therefore, it appears that precast concrete girders prestressed with stainless steel strands can be designed to satisfy all requirements of the AASHTO LRFD specifications, but they will likely fail due to rupture of strand. When the design of a precast concrete girder results in rupture of strand, the deformability of the girder may be increased by increasing the number of strands, up to a certain point. Furthermore, unless the design is controlled by the Service III limit state, the deformability can also be increased by decreasing the initial tensioning level. These issues are discussed in greater detail in the FDOT report.[1]

Work on this topic is ongoing as part of a research project for National Cooperative Highway Research Program Project 12-120, "Stainless Steel Strands for Prestressed Concrete Bridge Elements," which is to be completed in 2024. One goal of that project is to develop specifications for the design of prestressed concrete members using stainless steel strands. These specifications will be built on a broader understanding of requirements for ductility when using reinforcement materials with reduced ductility and will enable implementation of stainless steel strands at a national level.

References

1. Rambo-Roddenberry, M., and A. Al-Kaimakchi. 2020. *Stainless Steel Strands and Lightweight Concrete for Pretensioned Concrete Girders*. Tallahassee, FL: Florida Department of Transportation. https://rosap.ntl.bts.gov/view/dot/60647.
2. ASTM International. 2020. *Standard Specification for Low-Relaxation, Seven-Wire, Grade 240 [1655], Stainless Steel Strand for Prestressed Concrete*. ASTM A1114/A114M-20. West Conshohocken, PA: ASTM International.
3. ASTM International. 2018. S*tandard Specification for Low-Relaxation Seven-Wire Steel Strand for Prestressed Concrete*. ASTM A416/A416M-18. West Conshohocken, PA: ASTM International.
4. Al-Kaimakchi, A., and M. Rambo-Roddenberry. 2021. "Mechanical and Bond Properties of Grade 2205 Duplex High-Strength Stainless Steel Strand." *PCI Journal* 66 (4): 66–81. https://doi.org/10.15554/pcij66.4-01.
5. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.

Dr. Anwer Al-Kaimakchi, is a bridge designer with Corven Engineering, an H&H company, in Tallahassee, Fla. Dr. Michelle Rambo-Roddenberry, is a professor and associate dean for academic and student affairs at FAMU-FSU College of Engineering in Tallahassee, Fla.

CREATIVE CONCRETE CONSTRUCTION

Battery-Powered Reinforcing Bar Tying Technology Improves Efficiency and Reduces Repetitive-Use Injuries

by Mustafa Ali, MAX USA Corp.

About 30 years ago, the first battery-powered reinforcing bar tying tool was invented. These tools have been used successfully since 1993, saving money for general contractors by speeding up their tying work as well as reducing the risk for work-related injuries.

It is no surprise that construction workers face the potential for occupational injuries. From prefabrication yards to road and bridge construction, workers perform demanding functions that may require repetitive motions. These workers are often positioned in cramped conditions where they overexert their energy for eight-hour shifts or longer. Over time, the repetitious work of manually tying reinforcing bars can lead to carpal tunnel syndrome or back pain, which may force workers to take time off from work and lose wages. The incidence of injuries ranging from mild lower-back fatigue to severe musculoskeletal injuries results in incurred costs to contractors, including worker compensation claims, higher insurance rates, and even unforeseeable labor shortages.

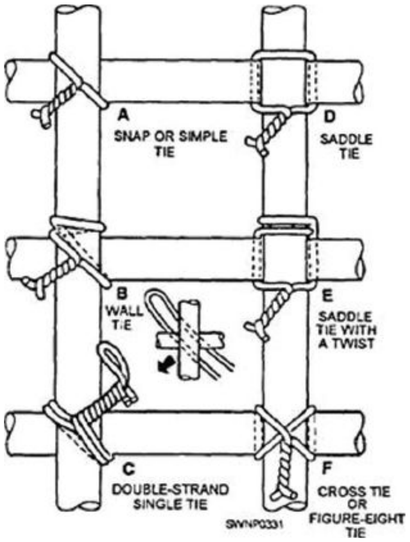
To reduce these risks, workers and employers can benefit from the enhanced development of battery-powered reinforcing bar tying tools available in the marketplace. From handheld options to stand-up reinforcing bar tying tools, workers can integrate this technology to avoid musculoskeletal injuries and fatigue from labor-intensive job functions. While the technology has not yet evolved to perform more complex ties such as saddle ties, these tools are an excellent option to quickly finish tedious snap ties.

The National Institute for Occupational Safety and Health (NIOSH) evaluated workers' risks of developing back and wrist disorders associated with tying reinforcing bar and the possible benefits of using a battery-powered tier (BPT) to prevent upper-extremity and lower-back musculoskeletal disorders on a particular project.[1] NIOSH concluded that the risk for developing a hand or wrist musculoskeletal disorder is reduced when a BPT or BPT+E (battery-powered tier and extension arm) is used. Using a BPT also lessens stress on the lumbar spine. Because only one hand is required to use a BPT, the free hand or arm is available to support the worker's upper body weight, which should reduce the compressive forces applied to the lumbar spine. Following the development of the extension arm, the first battery-operated stand-up reinforcing bar tying tool was introduced in 2020.

Reinforcing bar tying requires considerable labor; on average, it takes a worker 1 minute to complete five ties (12 seconds per tie). In contrast, a worker using a battery-powered reinforcing bar tying tool can secure a tie in approximately 0.5 seconds. Thus, a worker using a battery-powered reinforcing bar tying tool can expect to achieve an average of 17 ties per

An extension arm can be used to make a stand-up battery-operated reinforcing bar tier for horizontal applications such as bridge decks. Use of such tools may reduce the risk of occupational lower-back injuries. All Figures and Photos: MAX USA CORP.

A worker uses a handheld battery-powered reinforcing bar tier.



Battery-powered reinforcing bar tiers are an excellent option to quickly finish tedious snap ties; however, the technology has not yet evolved to perform more complex ties such as saddle ties.

minute, a rate that is more than three times faster than the unassisted rate. One of the fastest solutions available for tying no. 3 × no. 3 up to no. 7 × no. 7 reinforcing bars offers a wire coil with a minimum of 145 ties and a maximum of 265, providing 5000 ties per charge. Similarly, the battery-powered stand-up tool for tying no. 3 × no. 3 up to no. 6 × no. 6 reinforcing bars, provides a coil with a minimum of 155 ties and a maximum of 260, yielding 4600 ties per charge. These impressive statistics demonstrate that certain tasks on a construction project can be completed in record time.

Reference

1. National Institute for Occupational Safety and Health (NIOSH). 2005. *NIOSH Health Hazard Evaluation Report: Genesis Steel Services, Inc. Baltimore, Maryland*. HETA 2003-0146-2976. Washington, DC: NIOSH. https://www.cdc.gov/niosh/hhe/reports/pdfs/2003-0146-2976.pdf.

Mustafa Ali is a marketing executive for MAX USA Corp. in Plainview, N.Y.

An Update on the Concrete Bridge Engineering Institute

by Dr. Oguzhan Bayrak and Gregory Hunsicker, Concrete Bridge Engineering Institute

The Transportation Pooled Fund (TPF) for the Concrete Bridge Engineering Institute (CBEI) officially started in June 2023. Representatives from the 10 members of CBEI's Technical Advisory Committee recently participated in a kick-off meeting that was facilitated by the lead agency, the Texas Department of Transportation, and covered topics including introductions, scope, and schedule. The Technical Advisory Committee includes representatives from the Federal Highway Administration and state transportation agencies that are members of the TPF. Following the kick-off meeting, task groups are being formed to work on providing essential input into the planning and development of the various components.

Figure 1. Wick-induced bleed testing of freshly mixed grouts. On the left is a grout with excessive bleed water that failed the wick-induced bleed test. On the right is a grout with little bleed water that passes the wick-induced bleed test. Demonstrations such as this will be part of the hands-on training at the Concrete Bridge Engineering Institute. Photos: Concrete Bridge Engineering Institute.

The current CBEI schedule aims for the Concrete Materials for Bridges program to commence in early 2024, with instruction by Dr. Kevin Folliard, Dr. Thano Drimalas, and visiting instructors. The program will engage participants in group projects, tours of outdoor concrete durability exposure sites, and other activities, as outlined in the Winter 2023 issue of *ASPIRE*®. The launch of the Bridge Deck Construction Inspection program is scheduled for late 2024 (for program content see the Summer 2023 issue of *ASPIRE*). Dr. Elias Saqan recently joined CBEI and is primarily focused on the Bridge Deck Construction Inspection program. He is an excellent addition to the team and we are excited to have him on board. The Post-Tensioning Academy is scheduled to be available in late 2025. The CBEI TPF is scheduled to run through May 2027, after which time CBEI and these programs are expected to be self-sustaining.

Hands-on learning is critical to all three pillars of CBEI—concrete materials, bridge deck construction inspection, and post-tensioning. CBEI staff, through their formal education and professional experience in teaching, understand the value of hands-on learning in engineering education and, in particular, bridge engineering. For example, those of us who participated in the American Segmental Bridge Institute's (ASBI's) Grouting certification classes and the Post-Tensioning Institute's (PTI's) Levels 1 & 2 Multistrand and Grouted PT curriculum have witnessed firsthand the importance of hands-on learning and the impact that it has on students and trainees.

One of the key topics taught during post-tensioning grouting instruction is the issues that can be caused by the development of bleed water and the resulting voids and/or intermediate bleed lenses. The importance of using an engineered zero-bleed grout, such as a prepackaged propriety mixture, and using the correct water addition (never exceeding the maximum amount of mixing water) are covered extensively and stressed throughout all grouting classes. One of the most effective demonstrations to convey this point is performing a wick-induced bleed test on two types of grout (**Fig. 1**). In our case, a Class C prepackaged proprietary zero-bleed grout and a Class A cement-water grout were mixed and tested alongside each other. Within three hours of the mixing, excessive bleed water was identified within the Class A cement-water grout, whereas minimal bleed water was exhibited by the Class C prepackaged proprietary zero-bleed grout. Seeing the bleed water accumulate in real time was impactful and memorable.

To bring positive aspects of hands-on learning into the CBEI curriculum, the programs will emphasize engagement, accelerated learning, retention, and assessment. Interactive demonstrations and group exercises are designed to engage attendees and create an enriching environment with team interaction. Accelerated learning is provided by simulating real-world examples using a variety of procedures and demonstrating common defects, which effectively compresses years of field experience into short modules. Impactful demonstrations are designed to illustrate key concepts that participants will remember and retain long after the course. Practical field assessments will measure attendees' understanding of topics, especially as they relate to certification programs. As CBEI staff, we are keenly aware that the agencies contributing to the pooled funding of CBEI also place high value on hands-on learning.

Special recognition and many thanks go to the participating agencies that have made this effort possible: the transportation agencies of Texas, Colorado, Florida, Georgia, Iowa, Michigan, Minnesota, Pennsylvania, and Utah, and the Federal Highway Administration. Thanks also go to our industry partners for their continued support and engagement: ASBI, PCI, PTI, and the members of the National Concrete Bridge Council.

Dr. Oguzhan Bayrak is a chaired professor at the University of Texas at Austin, where he serves as the director of the Concrete Bridge Engineering Institute. Gregory Hunsicker is a research engineer at the University of Texas at Austin and deputy director of the Concrete Bridge Engineering Institute.

South Carolina

by Terry Koon, Hongfen Li, and John Caver, South Carolina Department of Transportation

Unbeknownst to many, South Carolina is home to the fourth largest state-owned highway system in the United States, with approximately 41,500 miles of roadways and 8400 bridges. According to the 2020 U.S. Census, South Carolina is the third fastest-growing state, putting additional strain on the existing infrastructure.

In the past decade there has been a dramatic increase in funding for an aggressive interstate improvement program, as well as for road safety and maintenance programs, with nearly 200 bridges constructed and another 75 under construction in South Carolina. Despite all the headway, a surge in bridge funding is needed over the next decade.

Design Standards and Challenges

Of the 8400 state-owned bridges, more than 1700 are over 60 years old; approximately 1150 of them were built more than 75 years ago and are rapidly approaching the time for replacement or repair. As part of a 10-year bridge replacement effort and to help standardize and guide the design and construction of current and future bridge projects, policy documents such as the South Carolina Department of Transportation's (SCDOT's) *Bridge Design Manual*,[1] *Bridge Drawings and Details*,[2] and *Seismic Design Specifications for Highway Bridges*[3] are under contract to be updated.

Bridge designs in South Carolina have to address challenging environmental conditions such as the following:

- **Marine environment**. Along the South Carolina coast, corrosion due to saltwater exposure is a big issue. Given the relatively flat topography of the coastal area, bridges are often built near the water. These bridges are exposed to salt intrusion into the concrete substructures, support members, and the bottoms of concrete decks. This corrosion risk is a constant threat to bridge durability and longevity. SCDOT is currently evaluating ways to extend the service lives of bridges in these environments.
- **Hurricanes**. Hurricanes are a constant threat for the SCDOT infrastructure system, especially along the coast. Wind is a definite hazard to be considered in bridge design; however, storm surge, inland flooding, and embankment or substructure scour cause the greatest concern.
- **High seismic-risk areas**. South Carolina is considered one of the highest seismic-risk areas on the East Coast. SCDOT has incorporated seismic design and detailing requirements for new bridge construction since before 2001. Incorporating accelerated bridge construction (ABC) with precast concrete construction is challenging because proven high-seismic connections between ABC bridge components are still emerging. The potential for soil liquefaction is another challenge when designing any bridge to withstand anticipated seismic forces and displacements.

The revised policies and guidelines will assist the design work of both SCDOT staff and outside consultants in designing for both challenging

A design-build contract was awarded in April 2023 for a project to replace Interstate 20 bridges over Wateree River and rehabilitate Wateree Swamp overflow bridges in Kershaw County. Shown here are existing spans carrying the interstate. All Photos: South Carolina Department of Transportation.

Secondary Route 770 Bridge over Hanging Rock Creek used modified Northeast Extreme Tee D beams (in foreground) in one end span; prestressed concrete cored slabs in the two center spans; and prestressed concrete solid slabs in the other end span. The structure is being monitored to evaluate the performance of the various types of beams and connection details.

and relatively routine conditions. The intent is not to limit staff and consultants from innovating, but rather to encourage more cost-effective and technically sound solutions. The new standards will conform to the ninth edition of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[4]

Design Templates

For the replacement of low-volume crossings, SCDOT is using bridge design templates to expedite project development and drawing details. The agency encourages consultants to use these accepted means and methods when designing short slabs, box beams, and other simple spans. This approach is similar to other states' efforts to update and standardize current practices, avoid redundancies, and accelerate project development. The template concept is intended to speed up the time to contract award for repetitive-type structures.

In addition to standardizing design practices, SCDOT is also standardizing bridge components. Many local precasters maintain Florida I-beam (FIB) forms and other girder sections common in the region. SCDOT has been using FIBs and similar girder shapes for years, which helps with consistency, especially on the alternative delivery side. The same applies to bulb-tee sections, which were modified for SCDOT's preferred shapes and sizes.

Modified NEXT D Beam

SCDOT typically relies on solid and hollow precast, prestressed concrete beams with conventional grouted keyways for bridges with low traffic volumes. However, the longitudinal shear keys of many of South Carolina's bridges have deteriorated, resulting in reflective cracking in the bridge decks. This deterioration can be costly because water can migrate through the cracks and corrode the beam's reinforcement and prestressing strands, leading to the need for repairs and shortening service life.

To combat this durability issue, SCDOT teamed with Clemson University to investigate more-durable alternatives. Their research led to a viable alternative that could be used with ABC: a modified Northeast Extreme Tee (NEXT) D beam with ultra-high-performance concrete (UHPC) connections. The smallest standard NEXT D beam is 28 in. deep with webs spaced at 5 ft, whereas the modified NEXT D beam has a depth of 21 in. and a web spacing of 3 ft.

Since 2016, bridge replacement projects have been used to evaluate how the performance of the modified NEXT D beam sections with the UHPC closure pours compares with that of traditional cored- or solid-slab sections with grouted shear keys. On the four-span Secondary Route 770 Bridge over Hanging Rock Creek replacement project, 21-in.-deep, 40-ft-span modified NEXT D beams were used for one end span; 24-in.-deep, 70-ft-span prestressed concrete cored slabs comprised the center spans; and 21 in.-deep, 40-ft-span prestressed concrete solid slabs were used on the other end span. Three different types of longitudinal connections were used, but each type used UHPC. The superstructure and longitudinal connections are being monitored, and a report of the findings has been released.[5]

Among the lessons learned from the construction side of the project are the following:

- **UHPC is presently expensive.** With the development of more UHPC mixture options, the cost should decrease. There was only one manufacturer of UHPC at the time of the project. A proprietary UHPC mixture was used instead of attempting to use a mixture with local materials.
- **Watertight seals are critical for UHPC installation**. Given the flowable nature of UHPC, watertight seals are needed for forming to ensure no loss of material before the concrete hardens.
- **Crews must take safety precautions when handling UHPC mixtures**. Respiratory protection is required when mixing. The steel fibers are sharp, and exposed fibers need to be handled carefully.

Deterioration of longitudinal shear keys is a durability issue for many of South Carolina's bridges. Hoping to avoid such deterioration in the future, the South Carolina Department of Transportation teamed with Clemson University and developed a modified Northeast Extreme Tee (NEXT) D beam with ultra-high-performance concrete (UHPC) longitudinal connections that can be used for accelerated bridge construction. The reinforcement projecting from the top flange will be encapsulated in an 8-in.-wide UHPC closure pour.

Rendering of the proposed bridge crossing Mackay Creek, part of the U.S. Route 278 corridor providing the sole link between Bluffton, S.C., on the mainland and Hilton Head Island. The new structure would provide a new six-lane roadway that would meet the current seismic design standards and increase safety along the route.

- **Larger closure pours are beneficial**. Installation of UHPC is easier in wider closure pours of the NEXT D beams compared with the typical narrow opening used for cored-slab shear keys.
- **Quality-control/quality-assurance provisions should be developed specifically for UHPC**. SCDOT used a prequalification specification for acceptance of the UHPC mixture but did not have standard quality-control procedures for installation, sampling, and curing of concrete. Standard requirements for typical concrete mixtures were not adequate.

Alternative Delivery

After the successful completion in 2005 of the Arthur Ravenel Jr. Bridge in Charleston, S.C., the SCDOT design-build program was initiated. A dedicated group was established to oversee alternative delivery and all design-build projects in the state. Although design-build contracts account for a much larger portion of the funding for bridge work currently under contract in South Carolina, design-bid-build bridge replacements are still an important and necessary part of the bridge program for SCDOT. SCDOT needs both contract methods to keep a variety of large and small bridge contractors working in South Carolina and to improve the overall condition of the state's bridge inventory.

Most of the time, design-build contracts gain efficiencies and cost savings and enable the team to move through the design phase faster. SCDOT encourages innovation through the alternative technical concept process and scores added value as part of its best-value criteria. New bridge types, materials, and methods are discussed privately with proposers and vetted by a multidisciplinary team of engineers during procurement. Some innovations are carried forward into requests for proposals for future projects.

SCDOT is also achieving increased efficiencies through bundled bridge arrangements. Under the Closed and Load-Restricted Bridge Program, the agency annually awards several bridge packages grouped by type, complexity, and location. The number of bridges in a bundle ranges from 4 to 16, depending on industry availability, feedback, and determination of how to maximize efficiency. Certain low-volume routes qualify for less-stringent design criteria, whereas primary route bridges are grouped together because of their greater complexity. The design-build teams bring their expertise as well as means and methods to the table, adding value, innovation, and cost savings through a collaborative approach. Concrete cored slabs and box beams are typically the bridge design of choice for low-volume routes, whereas concrete beam bridges with cast-in-place concrete decks are used most often on main routes for durability and reduced maintenance costs. ABC concepts are also encouraged.

Carolina Crossroads

The Carolina Crossroads project is the largest design-build project in the state to date. With a budget of more than $2 billion over five phases, the infrastructure project encompasses 43 new bridges, 7 reconstructed interchanges, and 132 new lane miles that will take 9 years to complete.

Because costs were projected to exceed $1.5 billion for the first half of the program, the mega-project was split into sections to accommodate the bonding capacity of contractors. The first two of five phases are currently under construction. Phase 1 includes the construction of a new full-access interchange at Colonial Life Boulevard to improve traffic flow by removing the weave on Interstate 26 (I-26) westbound between Interstate 20 (I-20) and Interstate 126 (I-126). This phase is also lengthening the I-26 eastbound exit ramp to U.S. Route 378/Sunset Boulevard to prevent stopped vehicles on the interstate shoulders. Phase 2 improves access for vehicles moving from I-20 westbound to I-26 westbound and enhances the Broad River Road interchange at I-20. Phase 3 includes a system-to-system interchange in Columbia, S.C., and will be awarded at the end of 2023. Phases 4 and 5 include the widening of I-26 north of the interchange with I-126; these will be design-bid-build projects that will be constructed after earlier phases are completed.

Recent and Current Projects

A major bridge replacement project, the 20-span, 3340-ft-long U.S. Route 21 Harbor River Bridge in Beaufort County, was opened to traffic in April 2021. The bridge, which connects the mainland to several islands, is designed to withstand tidal action, hurricane-force winds, seismic events, vessel collisions, and significant long-term scour, while preserving the environmentally sensitive and picturesque setting. (The Harbor River Bridge is featured in the Summer 2023 issue of *ASPIRE*®.)

As additional funding becomes available, SCDOT is also advancing large (more than $100 million) interstate bridge replacement projects over major rivers and lakes. The first project is the replacement of eastbound and westbound bridges of I-20 over the Wateree River in Kershaw County. It features a 1515-ft-long, 11-span river-crossing bridge with a cast-in-place reinforced concrete deck supported on prestressed concrete FIB girders.

A project to improve Interstate 95 (I-95) over the Great Pee Dee River system near Florence, S.C., was recently awarded a federal planning grant, and work has started on a feasibility study to determine the number of bridges that will be replaced in the 7-mile-long floodplain. The grant money will allow SCDOT to mitigate the effects of flooding on bridges along this major hurricane evacuation route for residents and visitors along the coast.

Preliminary engineering for I-95 over Lake Marion in Santee, S.C., is underway to replace twin bridges, more than 4500 ft long, that bisect the lake. The goal is to get ahead of the replacement timeline for these critical lifeline structures, built in the 1960s and 70s, before they require load posting.

Future Project

SCDOT is embarking on a project to improve the U.S. Route 278 corridor between Bluffton and Hilton Head Island. The purpose of the project

The U.S. Route 21 over Harbor River replacement bridge in Beaufort County used Florida BT-78 beams. The 3350-ft-long, high-level structure replaced an 80-year-old swing-span bridge over a tidal waterway and navigable channel.

is to address structural deficiencies in existing structures and reduce congestion. The proposed six-lane, 7264.5-ft-long structure would connect the mainland to Hilton Head Island and include access ramps for Pinckney Island National Wildlife Refuge. The new structure would cross Mackay Creek and Skull Creek, providing a new six-lane roadway that would meet the current seismic design standards and increase safety along this route.

The superstructure would consist of 45 prestressed concrete beam spans combined into 13 continuous units. Florida I-beams are proposed for all but three spans, with spans ranging from 120 to 171.5 ft. Crossing Skull Creek, which is part of the Intracoastal Waterway, created more of a challenge. The three-span—225, 280, and 225 ft—continuous unit over the Skull Creek channel will consist of haunched, spliced and post-tensioned, prestressed concrete modified AASHTO bulb-tee beams. Construction on the project is scheduled to start in early 2024.

Digital Project Delivery

SCDOT has moved to a digital delivery system and accepts only electronic submissions for all plan sets including review submittals, sealed plans, and shop drawings. This move has facilitated better collection and use of data for project management, including the use of digital as-builts. Transitioning from traditional paper-based workflows has helped the agency accumulate information for future use.

The agency currently maintains a searchable online inventory of as-built records that handles more than 700,000 searches per year and contains as-built records dating back almost 100 years. More than 2.5 million plan sheets are available online. New project as-builts are submitted as digital PDFs with advanced features such as searchable text, vector graphics, and layers of information for easier navigation.

South Carolina looks to the future with its comprehensive plan to address highway safety, structurally deficient bridges, and an aggressive interstate program. The state is making significant strides toward improved infrastructure that supports continued growth.

References

1. South Carolina Department of Transportation (SCDOT). 2006. *SCDOT Bridge Design Manual*. Columbia, S.C.: SCDOT. https://www.scdot.org/business/pdf/structural-design/SCDOT_Bridge_Design_Manual.pdf.
2. SCDOT. 2020. *Bridge Drawings and Details*. Columbia, S.C.: SCDOT. http://info2.scdot.org/structuraldesign/Pages/BridgeDrawings.aspx.
3. SCDOT. 2008. *SCDOT Seismic Design Specifications for Highway Bridges*. Columbia, S.C.: SCDOT. https://www.scdot.org/business/pdf/structural-design/specs_2008.pdf.
4. American Association of State Highway and Transportation Officials (AASHTO). 2020. AASHTO *LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.
5. Ross, B., and T. Cousins. 2019. *Performance Evaluation of the SCDOT NEXT-D Beam Bridge*. Clemson, S.C.: Clemson University. https://www.scdot.scltap.com/wp-content/uploads/2019/09/Final-Report.pdf.

Terry Koon is structural design support engineer, Hongfen Li is structural policy design engineer, and John Caver is alternative delivery structural engineer for the South Carolina Department of Transportation in Columbia.

The five-phase Carolina Crossroads project is one of the largest construction ventures in South Carolina. It is designed to alleviate congestion along 14 miles of the Interstate 20, 26, and 126 corridor in Columbia, S.C. This ramp from Interstate 26 to westbound Interstate 126 uses a combination of cast-in-place and precast concrete bridge components.

A PROFESSOR'S PERSPECTIVE

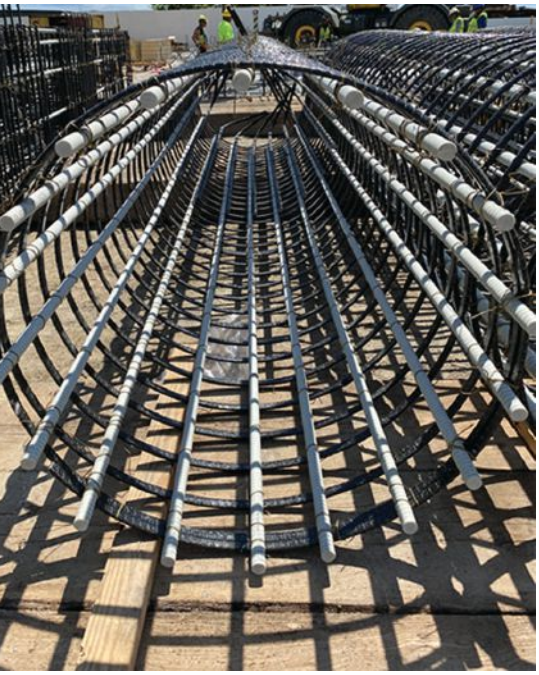
Fiber-Reinforced-Polymer Reinforced and Prestressed Concrete

A new, but no longer emerging, technology

by Dr. Gregory Lucier and Dr. Rudolf Seracino, North Carolina State University

When it opens to the public in late 2023, the Harkers Island Bridge in Carteret County, N.C., will be the premier example of a prestressed concrete structure reinforced exclusively with fiber-reinforced-polymer (FRP) reinforcement. (See the Project article in this issue of *ASPIRE*®). The 3200-ft-long, 28-span bridge, which is currently under construction, will use only two types of composite FRP reinforcement for the piles, caps, columns, girders, and deck. Internal steel reinforcement was replaced in favor of glass-fiber-reinforced-polymer (GFRP) and carbon-fiber-reinforced-polymer (CFRP) composite reinforcements to create a bridge that will withstand the harsh saltwater environment with little maintenance over a design life of at least 75 years. Because there is no internal steel to corrode and the GFRP and CFRP internal reinforcements are not sensitive to chlorides, common degradation mechanisms are eliminated.

Glass-fiber-reinforced-polymer (GFRP) reinforcement cage for a cast-in-place concrete pier column. Bends in GFRP must be formed during manufacturing; GFRP cannot be bent on site. All Photos: North Carolina State University.



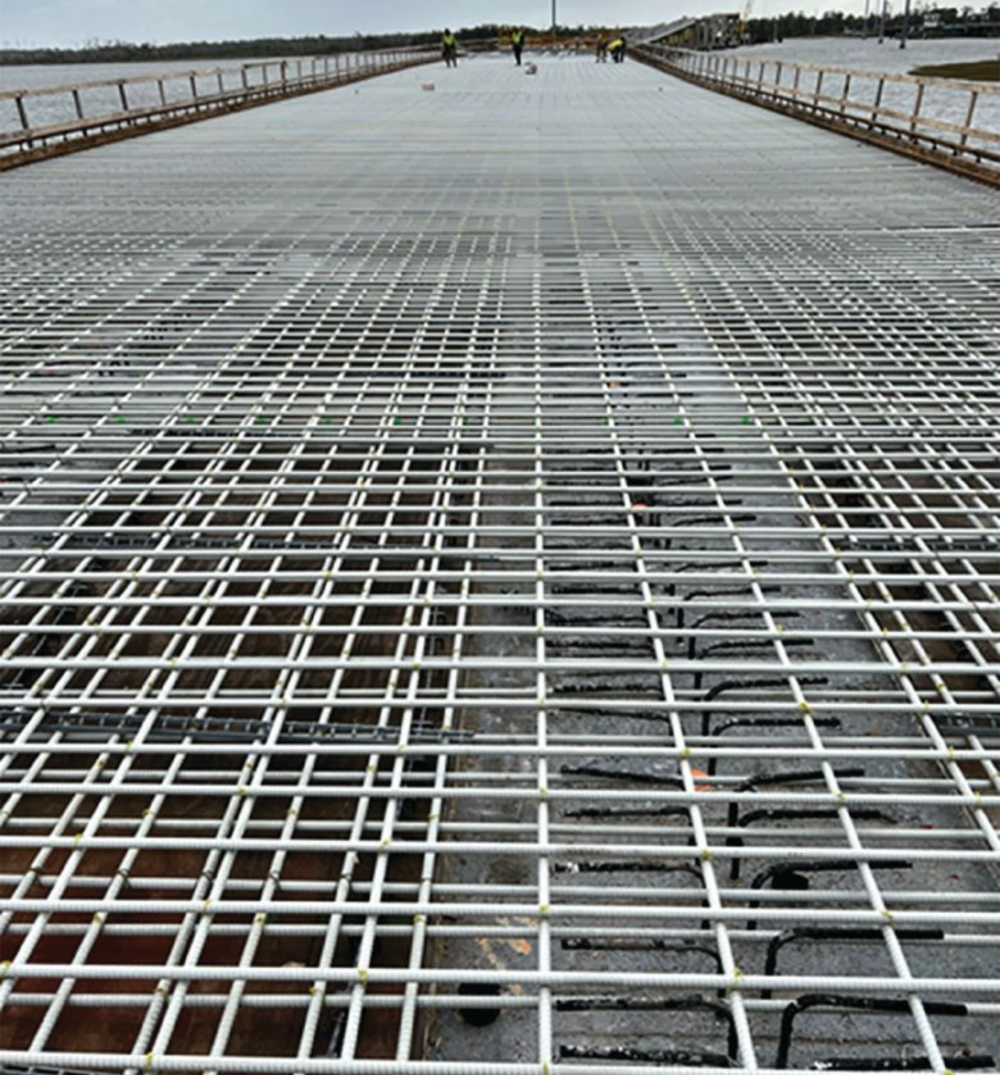
The current route serving Harkers Island consists of two prestressed concrete bridges joined by a small island. Both structures are just over 50 years old, but constant exposure to saltwater, including spray and splash onto the low-lying superstructures, has taken a toll on the internal steel reinforcement, and signs of corrosion are omnipresent. As the only link between Harkers Island and the mainland, it is especially important for the new bridge to be a reliable and durable piece of infrastructure on which the community can depend. The use of internal FRP reinforcement in the new bridge will help ensure that the bridge remains open and in good condition.

Two types of internal FRP reinforcement are used in the substructure and superstructure. Piles and girders are prestressed with longitudinal 0.6-in.-diameter CFRP strands. The 24-in.-square piles have transverse CFRP square spiral confining the strands, and the 54-, 72-, and 78-in.-deep Florida I-beam girders have GFRP bars for transverse and shear reinforcement. Cast-in-place concrete caps, columns, and bridge decks are reinforced with cages and mats of GFRP bars, spiral, and stirrups. In general, the strand and bar sizes, shapes, and spacing are similar to those commonly used with traditional steel reinforcement. However, the amount of FRP material used typically is slightly more than the amount of steel reinforcement it replaces. The specific reason for this difference in reinforcement amounts depends on the design action considered. In some cases, because FRP material is less stiff than steel, more FRP reinforcement is required. This is particularly the case when serviceability (such as deflection) controls. In other cases, conservative limits in design guides and codes may limit the allowable tensile force in FRP bars.

CFRP strands are shipped to the precast concrete plant on spools, in a similar fashion to traditional steel strand, although special chucks must be used to grip the CFRP.

Any FRP reinforcement—glass or carbon—that needs bends is preformed

Glass-fiber-reinforced-polymer reinforcement has been placed for a pile cap. After installing the side forms, the concrete will be placed.



Glass-fiber-reinforced-polymer reinforcement was used in a cast-in-place concrete bridge deck and for the stirrups, which can be seen protruding from the prestressed concrete Florida I-beam girders.

to the required shapes before delivery to the precast concrete plant or jobsite. FRP reinforcement cannot be field bent; it must be formed to the desired shape as the polymer matrix initially cures. All FRP reinforcement—both glass and carbon—is approximately five times lighter than the steel it replaces, so shipping and handling are easier and more economical. FRP is generally stronger (with a higher tensile strength), but less stiff, than the equivalent steel it replaces, and designers must account for these variables in the design process.

It is important to recognize that when the North Carolina Department of Transportation (NCDOT) decided to build the $60 million all–FRP reinforced bridge replacement, the agency drew upon knowledge derived from decades of research, as well as design guidance and specifications from the American Association of State Highway and Transportation Officials (AASHTO) and the American Concrete Institute (ACI).[1–3] Committees at AASHTO, ACI, and PCI have focused on internal FRP reinforcement for years.

While large-scale concrete structures reinforced with GFRP bars and prestressed with CFRP strands may be new to many readers, the technology is proven, tested, codified, and reliable. The key benefits of internal FRP reinforcement, which include greater durability, longer design life, and substantially reduced maintenance, have been demonstrated.[4] FRP-reinforced concrete bridges have been successfully in service in Japan since 1988, in Canada since 1997, and in the United States since 2001. NCDOT constructed a GFRP-reinforced bridge deck in 2005 and has actively funded research on concrete prestressed with CFRP strands since 2014.

Despite the extensive documented record regarding internal FRP reinforcement, extra steps are being taken on the Harkers Island Bridge to ensure quality. NCDOT has set up the testing and certification programs at each FRP reinforcement manufacturer. Additionally, quality-control tests are being conducted independently at North Carolina State University (NCSU) on FRP strands and bars randomly sampled from the precast concrete plants and the jobsite. NCSU's test results are compared with manufacturers' results and with design values. Randomly sampled bent FRP bars from the precast concrete plants and the jobsite are being tested in tension after being embedded in concrete to evaluate the quality of the bends. So far, all test results exceed design requirements.

The Harkers Island Bridge replacement project is an outstanding example of how the new, but proven, technology of internal FRP reinforcement can be successfully implemented at a large scale to create durable infrastructure.

NCSU students have the opportunity through the Deparment of Civil, Construction, and Environmental Engineering to learn from projects such as the Harkers Island Bridge replacement and the complementary research projects being performed on FRP materials. For example, undergraduate civil and construction engineering students study the behavior of GFRP reinforcing bars in the Civil Engineering Materials course, and they are introduced to GFRP reinforced concrete in the Reinforced Concrete Design course. At the graduate level, students can learn about FRP repairs in the Strengthening and Repair of Concrete Structures course.

Graduate students have the opportunity to lead original, state-of-the-art research projects associated with actual construction projects. They interact directly with bridge engineers, contractors, manufacturers, and inspectors throughout the project, gaining first-hand perspectives from all stakeholders. These experiences prepare them to be well-rounded engineers upon graduation.

Undergraduate research assistants also contribute to the projects. They participate in research while at the same time observing the design and construction process of an in-progress project.

Before a Florida I-beam girder is cast at the plant, prestressed carbon-fiber-reinforced-polymer strands and glass-fiber-reinforced-polymer transverse reinforcement are placed. Students at North Carolina State University have the opportunity to participate in research projects associated with actual construction projects.

References

1. American Association of State Highway and Transportation Officials. 2019. *AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete*. 2nd ed. Washington, DC: AASHTO.

2. AASHTO. 2018. *Guide Specification for the Design of Concrete Bridge Beams Prestressed with Carbon-Fiber-Reinforced Polymer (CFRP) Systems*. Washington, DC: AASHTO.

3. American Concrete Institute (ACI). 2022. *Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary*. ACI CODE-440.11-22. Farmington Hills, MI: ACI.

4. Benzecry, V., J. Brown, A. Al-Khafaji, R. Haluza, R. Koch, M. Nagarajan, C. E. Bakis, J. J. Myers, and A. Nanni. 2019. "Durability of GFRP Bars Extracted from Bridges with 15 to 20 Years of Service Life." ACI Foundation website. https://www.acifoundation.org/Portals/12/Files/PDFs/GFRP-Bars-Full-Report-with-Addendum.pdf.

SFA
SILICA FUME ASSOCIATION

The Silica Fume Association (SFA), a not-for-profit corporation based in Delaware, with offices in Virginia and Ohio, was formed in 1998 to assist the producers of silica fume in promoting its usage in concrete. Silica fume, a by-product of silicon and silicon based alloys production, is a highly-reactive pozzolan and a key ingredient in high-performance concrete, dramatically increasing the service-life of concrete structures.

The SFA advances the use of silica fume in the nation's concrete infrastructure and works to increase the awareness and understanding of silica-fume concrete in the private civil engineering sector, among state transportation officials and in the academic community. The SFA's primary goal is to provide a legacy of durable, sustainable, and resilient concrete structures that will save the public tax dollars typically spent on lessor structures for early repairs and reconstruction.

The SFA is proud to announce the release of the 2nd Edition the Silica Fume User Manual

Originally published in 2005, and very well received by the Engineering Community, the document has been update including a new chapter added on Sustainability.

To get your copy please send an email to *info@silicafume.org today!*

Silica Fume User's Manual
Second Edition

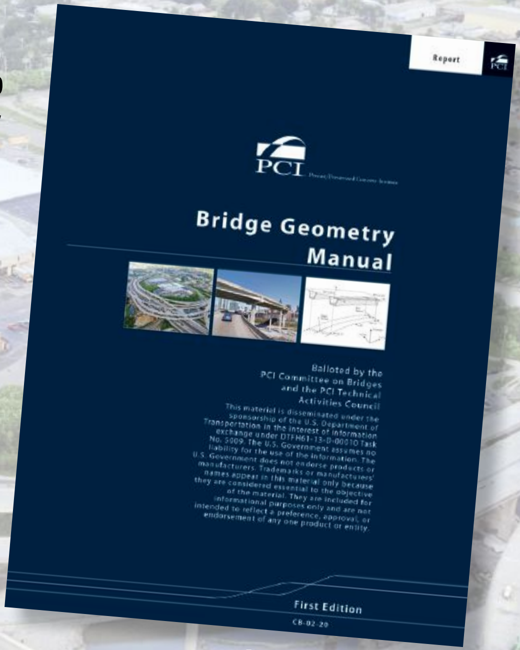
Building a Durable
Future Into
Our Nation's Infrastructure

For more information about SFA visit www.silicafume.org.

Bridge Geometry Manual

FREE PDF (CB-02-20)

The *Bridge Geometry Manual* has been developed as a resource for bridge engineers and CAD technicians. In nine chapters, the manual presents the basics of roadway geometry and many of the calculations required to define the geometry and associated dimensions of bridges. This manual and course materials are not linked to any software tool. The first five chapters are dedicated to the fundamental tools used to establish bridge geometry and the resulting dimensions of bridges. The vector-based approach to locating the north and east coordinates of a point defined by a horizontal alignment is then used to define the geometry of bridges. This manual includes the bridge geometry developed for straight bridges and curved bridges. The geometry of curved bridges using both straight, chorded girders and curved girders is presented. The PCI eLearning Center has 4 courses T505, T510, T515, and T517 for online training based on this publication.



Report

PCI Precast/Prestressed Concrete Institute

Bridge Geometry Manual

Balloted by the
PCI Committee on Bridges
and the PCI Technical
Activities Council

This material is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange under DTFH61-13-D-00010 Task No. 5009. The U.S. Government assumes no liability for the use of the information. The U.S. Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this material only because they are considered essential to the objective of the material. They are included for informational purposes only and are not intended to reflect a preference, approval, or endorsement of any one product or entity.

First Edition

CB-02-20

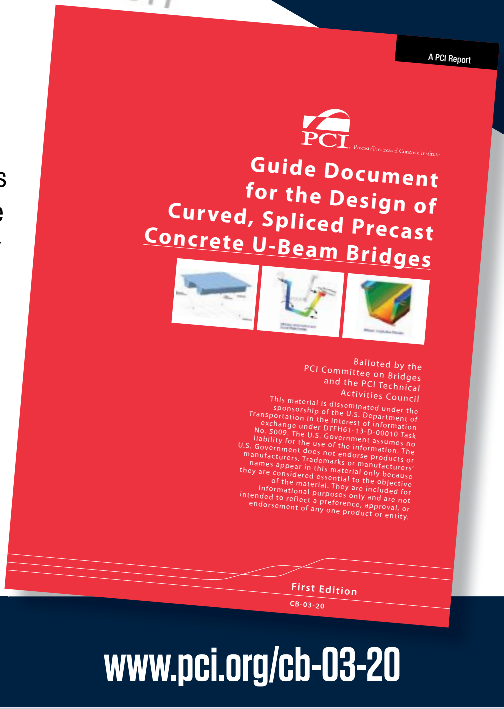
www.pci.org/cb-02-20

Guide Document for the Design of Curved, Spliced Precast Concrete U-Beam Bridges

FREE PDF (CB-03-20)

The *Guide Document for the Design of Curved, Spliced Precast Concrete U-Beam Bridges* has been developed as a resource for bridge engineers. In nine chapters, the guide documents the advancement of this bridge technology. This technology, which originated and progressed initially in Colorado over approximately 20 years, has evolved through the collaboration of designers, contractors, and owners. Much of the current technology is in its second or third generation. Agencies and builders have shown interest in replication of this bridge technology in several areas of the United States. However, there are certain areas of practice that have not been quantified. This has made it difficult for owners and the design community to fully embrace the technical solutions needed to design, construct, deliver, and maintain curved, spliced U-beam bridge systems. This document addresses those practices. The PCI eLearning Center has 4 courses T350, T353, T356, and T358 for online training based on this publication.

For more information on eLearning, visit page 64 of this issue.



A PCI Report

PCI Precast/Prestressed Concrete Institute

Guide Document for the Design of Curved, Spliced Precast Concrete U-Beam Bridges

Balloted by the
PCI Committee on Bridges
and the PCI Technical
Activities Council

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First Edition

CB-03-20

PCI Precast/Prestressed Concrete Institute

www.pci.org/cb-03-20

CONCRETE CONNECTIONS

Concrete Connections is an annotated list of websites where information is available about concrete bridges. Links and other information are provided at www.aspirebridge.com.

IN THIS ISSUE

https://www.hdrinc.com/portfolio/los-angeles-international-airport-automated-people-mover
The 2.25-mile-long elevated guideway for the Los Angeles World Airports' automated people mover (APM) at Los Angeles International Airport is the subject of the Project article on page 16. The APM guideway is a concrete segmental box-girder structure and is designed for seismic resiliency. This is a link to HDR's webpage for the project, which features photos, articles, and additional information.

https://www.ncdot.gov/projects/harkers-island/Pages/default.aspx
This is a link to the North Carolina Department of Transportation's project webpage for the Harkers Island Bridge, which includes links to project photos and videos. The bridge replacement project is the subject of the Project article on page 24 and is also discussed in the Professor's Perspective on page 54. The new Harkers Island Bridge is the first concrete bridge in North Carolina to be reinforced exclusively with glass-fiber-reinforced polymer and carbon-fiber-reinforced polymer composite reinforcement.

https://www.bimforbridgesus.com
The Transportation Pooled Fund project TPF-5(372) is a collaborative effort by more than 20 state departments of transportation, the Federal Highway Administration, and the American Association of State Highway and Transportation Officials Committee on Bridges and Structures to develop an open, national standard for building information modeling (BIM) for bridges and structures. This is a link to the TPF-5(372) website, which has links to case studies and other resources. BIM for bridges is the subject of the Perspective article on page 10.

https://www.fhwa.dot.gov/bridge/preservation/docs/hif22052.pdf
The service-life design of bridges is the topic of the Concrete Bridge Stewardship article on page 12 and the FHWA article on page 62. Much research has been conducted on the durability and service-life design of bridges in recent years, and the resulting guide publications include the Federal Highway Administration's *Service Life Design Reference Guide*, which is available at this link.

https://rosap.ntl.bts.gov/view/dot/35429
https://rosap.ntl.bts.gov/view/dot/35430
These are links to *Precast, Prestressed Concrete Bent Cap*, volumes 1 and 2. A research project conducted by the Texas A&M Transportation Institute studied the behavior of precast, prestressed bent caps and developed design and connection details, including examples. Designing efficient cross sections for precast concrete pier cap beams is the subject of the Concrete Bridge Technology article on page 38.

https://oasis.pci.org/Public/Catalog/Home.aspx?Search=piles&tab=2
The Perspective article about precast, prestressed concrete piles on page 34 mentions the free, on-demand webinar "Precast, Prestressed Concrete Piles" as a resource. That webinar is available on the PCI eLearning website at this link. Two new eLearning modules, T624: Overview of PCI's Recommended Practice for Prestressed Concrete Piles and T626: Application of PCI's Recommended Practice to Building Piles, can also be accessed at this same link.

https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/reports/fdot-bdv30-977-22-a.pdf?sfvrsn=c51de6aa_2
This is a link to the report for the Florida Department of Transportation–sponsored research project that investigated the use of 0.6-in.-diameter stainless steel strands in prestressed concrete I-girders. In addition to experimental findings, the report presents design guidelines for flexure. The flexural design of prestressed concrete girders using stainless steel strands is the topic of the Concrete Bridge Technology article on page 40.

https://www.scdotcarolinacrossroads.com
This website for the Carolina Crossroads project, which is mentioned in the State article featuring South Carolina on page 50, provides information and resources such as design visualization videos and construction photos. The Carolina Crossroads project is the largest design-build project in South Carolina to date.

Recently Approved Changes to the Ninth Edition *AASHTO LRFD Bridge Design Specifications*

by Dr. Oguzhan Bayrak, University of Texas at Austin

The 2023 meeting of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Bridges and Structures took place May 22–25 in Kansas City, Mo. During that meeting, seven working agenda items that impact Section 5, Concrete Structures, and Section 10, Foundations, of the *AASHTO LRFD Bridge Design Specifications*[1] were prepared by AASHTO Technical Committee T-10 and were approved by the Committee on Bridges and Structures (COBS). These agenda items were developed within the last year and follow the working agenda items that were approved in previous years for the forthcoming 10th edition of the AASHTO LRFD specifications.[2] They are T-10's last batch of changes for this edition, which is expected to be published in early 2024. This article summarizes the seven recently approved working agenda items. These items will be discussed in detail in upcoming issues of *ASPIRE*®.

High-Strength Steel in Concrete Bridges (Working Agenda Item 168, COBS Agenda Item 31)

The 2012 interim revisions to the AASHTO LRFD specifications permitted the use of high-strength reinforcing bars with a minimum yield strength of 100 ksi in nonseismic regions. High-strength reinforcing bars could be used for structures in nonseismic zones and, with some limitations, in moderate- to high-seismic zones. Article 20.2.1.3 in the American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)*[3] specifies additional requirements for ASTM A615[4] Grades 40, 60, 80, and 100 reinforcing bar and ASTM A706[5] Grades 60, 80, and 100 reinforcing bar. The requirements include the ratio of actual tensile strength to actual yield strength and elongations for use in designing reinforced concrete components. Some states have been using high-strength reinforcing bars, especially ASTM A706 Grade 80, in structural components, including capacity-protected components such as drilled shafts and cap beams. A large amount of material test data for ASTM A615 Grade 80 and Grade 100 and ASTM A1035[6] Grade 100 reinforcing bars has become available during the last decade. These data show that steel rolling mills have been manufacturing high-strength bars that meet the requirements of the material specifications.

This update allows the use of high-strength steel in a broader range of concrete bridge applications, which can result in cost savings while improving constructability. More specifically, the use of higher-strength steel could reduce component cross sections and reinforcement quantities, leading to savings in materials, shipping, and labor. Reducing reinforcement quantities will also reduce congestion problems, leading to better-quality concrete construction.

Reinforcement Detailing and Bar Cutoffs (Working Agenda Item 208, COBS Agenda Item 32)

Reinforcement termination and continuation requirements of the AASHTO LRFD specifications are summarized for better clarity through two new figures that will be added to the commentary for Article 5.10.8.1.2. One figure summarizes general flexural reinforcement termination requirements; the other summarizes negative-moment reinforcement termination requirements.

Clarifications for the Design of Segmental Concrete Bridges (Working Agenda Item 218, COBS Agenda Item 27)

Article 5.12.5, Segmental Concrete Bridges, is taken in large part from the AASHTO *Guide Specifications for Design and Construction of Segmental Concrete Bridges*.[7] These guide specifications, which were first published in 1989 and last revised in 2002, are out of date and have been archived. Many of the provisions in Article 5.12.5 are also out of date and need to be revised to achieve consistency with the current AASHTO LRFD specifications. In addition, this agenda item includes revisions to several articles not in Article 5.12.5 that are related to the design of segmental bridges. This update will make the design provisions for segmental concrete bridges more consistent with the remainder of Section 5.

The Design of Decks with Partial-Depth Precast Concrete Panels in Negative-Moment Regions (Working Agenda Item 226, COBS Agenda Item 28)

The AASHTO LRFD specifications do not clearly define the design and reinforcement for negative-moment regions of decks when stay-in-place precast concrete panels are used. This working agenda item is intended to provide guidance on deck reinforcement for continuous concrete girder applications such as spliced-girder bridges. For continuous steel girders, Article 6.10.1.7 of the specifications includes a limit for the deck reinforcement over which 1% reinforcement in two mats (two-thirds in the top and one-third in the bottom) is to be used. From the commentary, the reinforcement placement recommendation can be waived at the discretion of the engineer when precast concrete panels are used.

The current lack of specific guidance often leads to engineers making conservative and costly decisions on how to reinforce the deck in negative-moment regions. This agenda item offers the clarification that for decks with partial-depth precast concrete panels, the 1% reinforcement need only be calculated for the cast-in-place portion of the deck and placed in that portion. The proposed changes implement the recommendations of Ge et al.[8]

Clarifications for Post-Tensioned Concrete Bridges (Working Agenda Item 228, COBS Agenda Item 26)

The current requirements for post-tensioning systems and installation vary across the United States. As noted in National Cooperative Highway Research Program (NCHRP) Synthesis Report 562, *Repair and Maintenance of Post-Tensioned Concrete Bridges*,[9] results from a survey of bridge owners indicated that owners are referencing several specifications for post-tensioning, including the *AASHTO LRFD Bridge Construction Specifications*; PTI/ASBI M50.3, *Guide Specification for Multistrand and Grouted Post-Tensioning*; and PTI M55.1, *Specification for Grouting of Post-Tensioning Structures*.[10–12] The NCHRP report also noted that several states emulate the practices and specifications of other states. The report concluded that nonuniformity in post-tensionng specifications from state to state "is significant."

The goal of this agenda item is to establish consistent requirements for post-tensioning while making appropriate allowances for different protection levels (PLs) of post-tensioning systems. Variances in requirements—such as variances based on the aggressivity of the environment (that is, specifying a PL) or variances for regional requirements—are necessary and should be considered and included. Some variations, however, may represent relatively minor technical differences that can lead to issues related to misunderstandings or misinterpretations. The standardization of specifications in the post-tensioning industry has benefits; for example, it faciliates more widespread and effective training, as well as consistent inspection of post-tensioning systems and their proper installations. This two-part working agenda item references PTI/ASBI M50.3-19 and PTI M55.1-19. It also introduces changes to Sections 5 and 10 of the AASHTO LRFD specifications to align those sections with PTI/ASBI M50.3-19 and PTI M55.1-19, where differences exist, and to incorporate the PL concept on a national level.

Resources for Concrete Bridge Design and Construction (Working Agenda Item 229, COBS Agenda Item 30)

Resources for Concrete Bridge Design and Construction[13] is the first product developed under the collaboration agreement between AASHTO and the National Concrete Bridge Council (NCBC). This forthcoming document catalogs important resources for the design and construction of concrete bridges from AASHTO, the Federal Highway Administration (FHWA), NCBC member organizations, and selected other sources.

AASHTO LRFD Guide Specifications for Structural Design with Ultra-High-Performance Concrete (UHPC) (COBS Agenda Item 29)

AASHTO's forthcoming *Guide Specifications for Structural Design with Ultra-High-Performance Concrete*[14] is based on extensive research conducted by the FHWA, as well as research sponsored by PCI. T-10 developed the guide specifications through a year-long process of evaluation and revision, and it represents the best-known design guidance for nonprestressed and prestressed applications of UHPC. It is anticipated that material specifications compatible with the design provisions in the guide specifications will be ready for ballot in 2024.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications.* 9th ed. Washington, DC: AASHTO.
2. AASHTO. Forthcoming. *AASHTO LRFD Bridge Design Specifications.* 10th ed. Washington, DC: AASHTO.
3. American Concrete Institute (ACI). 2019. *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19).* Farmington Hills, MI: ACI.
4. ASTM International. 2020. *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*. ASTM A615/A615M-20. West Conshohocken, PA: ASTM International.
5. ASTM International. 2022. *Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement*. ASTM A706/A706M-22. West Conshohocken, PA: ASTM International.
6. ASTM International. 2020. *Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement*. ASTM A1035/A1035M-20. West Conshohocken, PA: ASTM International.
7. AASHTO. 1999. *Guide Specifications for Design and Construction of Segmental Concrete Bridges*. 2nd ed. Washington, DC: AASHTO.
8. Ge, X., K. Munsterman, X. Deng, M. Reichenbach, S. Park, T. Helwig, M. Engelhardt, E. Williamson, and O. Bayrak. 2021. *Designing for Deck Stress Over Precast Panels in Negative Moment Regions*. FHWA/TX-19/0-6909-1/5-6909-01-1. Austin, TX: Center for Transportation Research, University of Texas at Austin. https://library.ctr.utexas.edu/ctr-publications/5-6909-01-1.pdf.
9. Brenkus, N., G. Tatum, and I. Kreitzer. 2021. *Repair and Maintenance of Post-Tensioned Concrete Bridges*. Washington, DC: National Academies Press. https://doi.org/10.17226/26172.
10. AASHTO. 2017. *AASHTO LRFD Bridge Construction Specifications.* 4th ed. Washington, DC: AASHTO.
11. Post-Tensioning Institute (PTI) and American Segmental Bridge Institute (ASBI). 2019. *Specification for Multistrand and Grouted Post-Tensioning*. PTI/ASBI M50.3-19. Farmington Hills, MI: PTI.
12. PTI. 2019. *Specification for Grouting of Post-Tensioned Structures*. PTI M55.1-19. Farmington Hills, MI: PTI.
13. AASHTO. Forthcoming. *Resources for Concrete Bridge Design and Construction*. Washington, DC: AASHTO.
14. AASHTO. Forthcoming. *Guide Specifications for Structural Design with Ultra-High-Performance Concrete*. Washington, DC: AASHTO.

FHWA's *Service Life Design Reference Guide*

by Raj Ailaney, Office of Bridges and Structures, Federal Highway Administration

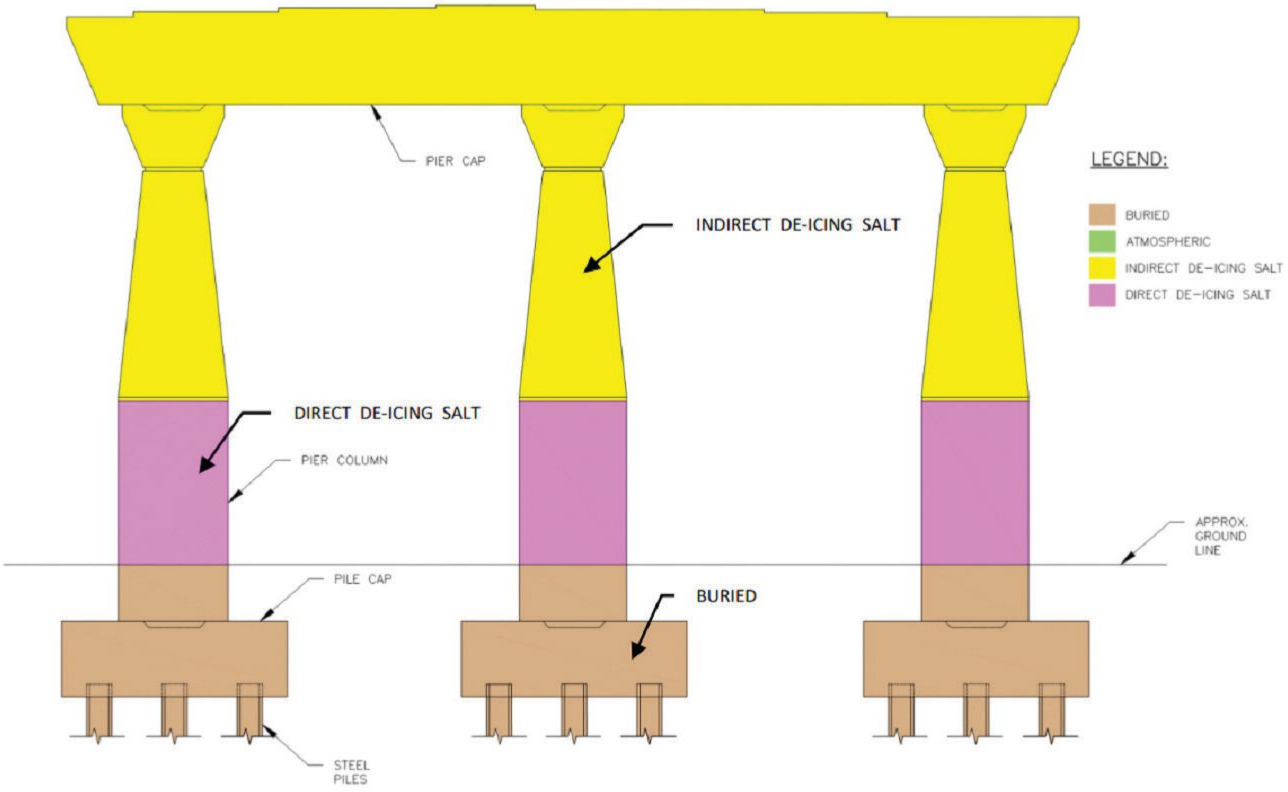
As our transportation infrastructure ages and inventories expand while budgets shrink, agencies realize that timely preventive maintenance and preservation activities are necessary to ensure the proper performance of transportation assets. Preventive maintenance and preservation enable state departments of transportation to increase the return on their infrastructure investment. With the implementation of Moving Ahead for Progress in the 21st Century Act (MAP-21) and Fixing America's Surface Transportation (FAST) Act, preservation is recognized as a vital component of achieving and sustaining a desired state of good repair of highway facilities. As such, preservation work is both eligible—Section 1103 of MAP-21 amended the definition of "construction" in 23 U.S.C. § 101—and encouraged under the National Highway Performance Program and the Surface Transportation Block Grant Program.

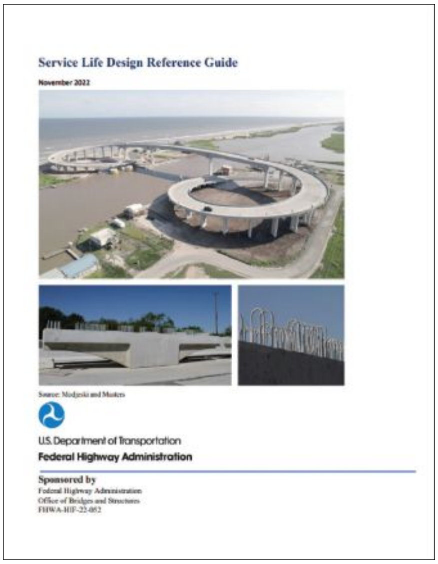
Improving infrastructure resilience is one of the U.S. Department of Transportation's strategic objectives.[1] While initial design for strength and serviceability is important to build a safe structure, it is equally important that there is a predefined strategy for preservation of bridge elements under environmental and operational loads so that the structure does not suffer capacity reduction. This preservation strategy contributes to the robustness of a structure and prolongs its service life. The Bipartisan Infrastructure Law, enacted on November 15, 2021, also provides support for activities that increase the resiliency of the National Highway System by making changes to the National Highway Performance Program (23 U.S.C. § 119(b)).

Service life design principles have been gaining broader acceptance as a tool to improve the performance of existing highway bridges and to design new bridges for enhanced durability. The objective of service life design is to assess the potential deterioration mechanism affecting structural elements, and to design those elements to achieve a target service life duration.

In the United States, the Second Strategic

The Federal Highway Administration's *Service Life Design Reference Guide*[5] identifies exposure zones for piers depending on atmospheric conditions, water levels, and direct or indirect exposure to deicing salts. All Figures: Federal Highway Administration.




Service Life Design Reference Guide

November 2022

Source: Modjeski and Masters

U.S. Department of Transportation
Federal Highway Administration

Sponsored by
Federal Highway Administration
Office of Bridges and Structures
FHWA-HIF-22-052

The Federal Highway Administration's *Service Life Design Reference Guide*[5] serves as a "road map" to service life design concepts and methods for bridge owners and designers.

Highway Research Program's research project R19A addressed the basis of service life design methodologies. Following that project, the National Cooperative Highway Research Program's 12-108 research project was initiated to create a specification for service life design principles and to demonstrate how the specification can be applied in typical design practice.[2] This project led to the publication of the American Association of State Highway and Transportation Officials' (AASHTO's) first *Guide Specification for Service Life Design of Highway Bridges* in 2020.[3]

With the longtime implementation of the *AASHTO LRFD Bridge Design Specifications*,[4] engineers have become accustomed to reliability-based design procedures for limit-state criteria such as strength, extreme event, service, and fatigue. Satisfying a limit-state design provides a calibrated way of ensuring that the designed resistance will exceed the design demand by an acceptably low probability of demand exceeding resistance.

Bridge durability can be treated in the same manner. Where possible, the new AASHTO guide specification creates a durability limit state in which the potential deterioration mechanism can be resisted by the proper combination of material properties and design details (for example, concrete cover, concrete mixture design, location of expansion joints, and deck drainage). This design approach leads to an acceptably low probability of end-of-service-life deterioration occurring before the bridge reaches the owner's desired target service life. To date, full-probabilistic models are limited, and the AASHTO guide specification only has a calibrated limit state for chloride-induced corrosion for concrete structures reinforced with uncoated reinforcing steel, so it uses deemed-to-satisfy provisions based on practical experience.

Implementing new specifications can be challenging. So far, only large signature structures and a few historic bridges have been designed for specific service life criteria. Our focus should be to design routine structures that use the concepts of service life design by applying site-specific environmental exposure conditions and/or performance requirements, so that they are designed for the durability and target service life that an owner desires.

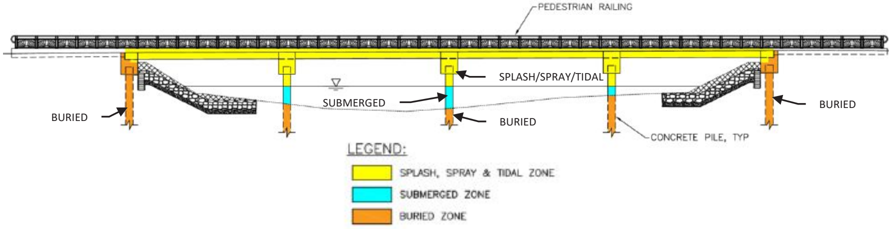
The Federal Highway Administration's (FHWA's) *Service Life Design Reference Guide*, published in November 2022, is a "road map" to service life design concepts and methods for bridge owners and designers.[5] This guide focuses on North American design practices and provides references for applying service life design principles to both concrete and steel highway bridges. It gives three examples for service life design that follow the information provided in the AASHTO guide specification.

On May 1, 2023, FHWA conducted a national webinar, "FHWA Service Life Design Reference Guide: How to Design Bridges that Last," with 42 states participating and more than 365 individuals in attendance. The webinar presented the available service life design methodologies, provided an overview of the new FHWA *Service Life Design Reference Guide*, and demonstrated the service life design process through an example. A recording of this webinar is available on the Bridge Preservation page of the FHWA website.[6]

Going forward, FHWA plans to conduct eight regional workshops, with the first occurring this fall and the series concluding in 2024. These workshops will be 1½ days long, specific to regional needs, and coordinated through the host state agency. They will be open to regional and state departments of transportation, consulting design engineers, and construction professionals.

When the service life of a structure is evaluted, both the locations of bridge components and the local climate are considered in the environmental classification outlined in the *Service Life Design Reference Guide*.[5]

Exposure Zone	Elements	Description
Tidal or Water- Level zone	• Top of Deck, • Soffit of Girders, • Bents, • Piles, • Barriers • Railing • Approaches	Not permanently submerged in the water, subject to wet-dry cycles, 20 ft above the tidal zone
Marine-Submerged	• Piles	Permanently submerged in sea water
Buried	• Piles • Abutments	Permanently buried in soil



References

1. Federal Highway Administration (FHWA). 2023. *FHWA Strategic Plan, FY 2022-2026*. FHWA-PL-23-010. Washington, DC: FHWA. https://highways.dot.gov/sites/fhwa.dot.gov/files/2023-05/FHWA_Strategic_Plan_05.25.23.pdf.
2. Murphy, T., T. Hopper, E. Wasserman, M. Lopez, J. Kulicki, F. Moon, A. Langlois, and N. Samtani. 2020. *Guide Specification for Service Life Design of Highway Bridges*. Washington, DC: National Academies Press. https://doi.org/10.17226/25672.
3. American Association of State Highway and Transportation Officials (AASHTO). 2020. *Guide Specification for Service Life Design of Highway Bridges*. Washington, DC: AASHTO.
4. AASHTO. 2020. *AASHTO LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.
5. Hopper, T., A.-M. Langlois, and T. Murphy. 2022. *Service Life Design Reference Guide*. FHWA-HIF-22-052. Washington, DC: FHWA. https://www.fhwa.dot.gov/bridge/preservation/docs/hif22052.pdf.
6. FHWA n.d. "Bridge Preservation." Accessed July 14, 2023. https://www.fhwa.dot.gov/bridge/preservation.


PCI
eLearning