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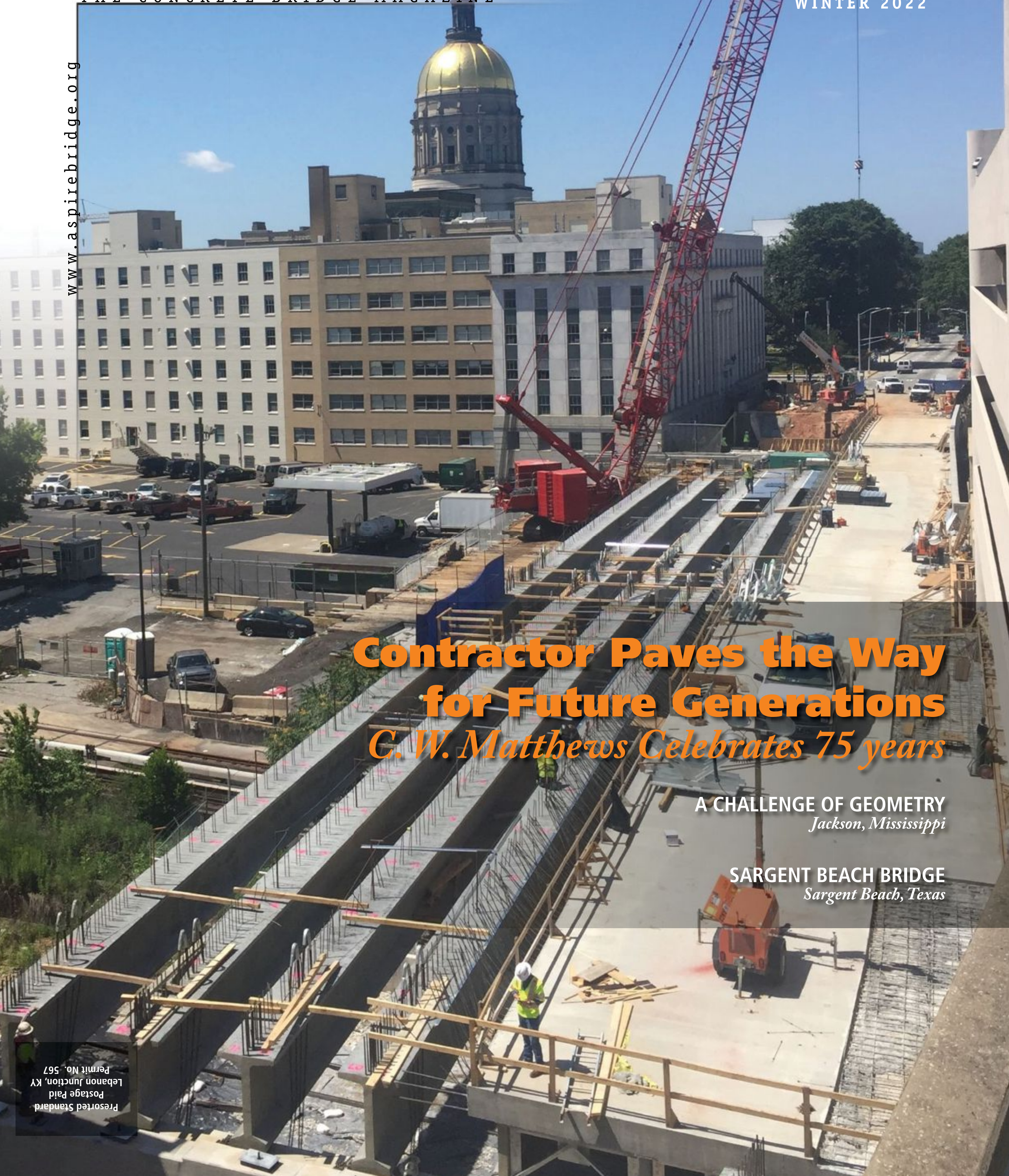

Contractor Paves the Way for Future Generations

C. W. Matthews Celebrates 75 years

A CHALLENGE OF GEOMETRY
Jackson, Mississippi

SARGENT BEACH BRIDGE
Sargent Beach, Texas

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Photo: Mississippi Department of Transportation.

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New Year, New Opportunities

William N. Nickas, *Precast/Prestressed Concrete Institute,* and Gregg Freeby, *American Segmental Bridge Institute*

Most people reflect on their past work accomplishments during their "routine" annual performance review, at the end of a project, or when there's a change to their operational environment. Such is the case for me now: my tenure as chair of the National Concrete Bridge Council (NCBC) is rapidly coming to a close, my operational environment is changing, and naturally I want to leave this posting in the best possible state for my successor. I'd like to think I've done a decent job of setting the scene for the next chair of NCBC.

A benefit of our organizational approach at the NCBC is that you usually have an idea of who your successor will be and, in all likelihood, you previously worked with that person. That is definitely the case here. Gregg Freeby is the incoming chair. He is one of the finest bridge engineers I've had the pleasure of working with, and I'm excited to announce his arrival in this role.

NCBC describes itself on its website (https://nationalconcretebridge.org) as a council of allied industry organizations dedicated to the following goals:

- Promote quality in concrete bridge construction.
- Gather and disseminate information on design, construction, condition, and repair of concrete bridges.
- Establish communication with federal and state departments of transportation, city and county public works departments, and consulting engineers.
- Provide information on behalf of the concrete industries to codes and standards groups.

NCBC is all about moving the industry forward, keeping concrete bridging solutions at the forefront. There is indisputably a variety of solutions to meet facility requirements, but no option is better than a structure built of concrete.

We've worked through several complex topics during these three fast-paced years: best practices for long spans using post-tensioned concrete; sharing resources related to technical concerns, professional engineer training, and construction jobsite personnel (among other issues); and advancing "open access" in an effort to share and demystify engineering concepts to achieve uniformity in knowledge dissemination and continuous improvement. (Notably, our achievements in knowledge dissemination and continuous improvement are rooted in knowledge development based on in-depth and exhaustive research.)

We focused energy on accelerated bridge construction, ultra-high-performance concrete, and durability. We collaborated with the Federal Highway Administration (FHWA) on the deployment of electrically isolated tendon technology and shared and incorporated innovative approaches to planning, design, and materials, along with unique construction processes, in an effort to stay one or two steps ahead of our industry. The challenge, as is the case for most things involving technological advancement, is to outpace the pace. In our profession, technological acceleration is often slowed, and rightfully so, by the most critical characteristic of our efforts—safety. In our eagerness to accelerate pace, we can never allow ourselves to undercut the serious nature of an engineer's inherent responsibility to deploy assets that serve the traveling public safely, minimizing risk while maximizing performance.

So today, Gregg and I want to share what's down the road, around the bend, or over the horizon for NCBC: Given today's tempo, what strategies and forward-looking approaches are required to leverage our engineering traditions and protocols?

We at NCBC would submit that the key is to focus our energies on three to five areas our members believe will most directly influence the success of their individual organizations as well as the success of NCBC and the concrete bridge industry as a whole. Additionally, our strategies need to be attainable by establishing goals not further out than five years. If we look beyond the five-year mark, we'll lose our stride and begin to wander, sputter, and fail to meet our members' needs. We won't lay out all areas on which we should focus, but here are some ideas.

One area of focus to consider is concrete bridge maintenance. Too often, our conversations shift to

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C. W. Matthews Contracting Co. Inc. used prestressed concrete beams to span the Metropolitan Atlanta Rapid Transit Authority and CSX railroad tracks for the Courtland Street project in downtown Atlanta.

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spicier topics. Life extension, strengthening, and stabilization often become sound bites in our discussions, but, honestly, they need our attention. Condition assessment and preservation are more important today than ever before.

Similarly, sustainability is a growing challenge for the transportation industry. However, solutions are already being deployed in the form of portland-limestone cements, which you will read about in this issue. Future conversations on sustainability will lead to discussions on life-cycle strategies, life-cycle assessments, and what makes up an environmental product declaration. This is yet another opportunity for our industry to lead.

Our organizational strength can, at times, weaken our core. We develop and provide a myriad of expertise, data, proven concepts, and techniques to our members, but sharing this information is too restricted in some cases. The idea of open access needs our attention—providing broader access to this important information will pay off in the long run.

Yes, we are absolutely suggesting openly sharing information, embracing multidisciplinary approaches, and being inclusive of a much wider audience. The idea is to bring the power of the entire bridge community together to dynamically influence the market. As a group of several engineering-focused nonprofit organizations, we must learn how to expand our work with other nonprofits for our mutual future successes. NCBC's affiliated organizations already embrace a multidisciplinary approach of openly sharing solutions to improve the construction environment. We suggest that NCBC exponentially expand this concept: what's good for some is much, much better for all.

Another critical component—some might argue that it is the single most important component—of our future success is to "get younger." The next time you attend a convention or meeting, take a moment to look around the room—I'm not the only one with stark white hair. Collectively, we are rapidly approaching the senior circuit. Our up-and-coming engineers often use data we've gathered, tested, checked, and published over the years with little thought as to how the pieces all came together. They have also changed everyone's expectations regarding access to information. For many young engineers, if information cannot be found via a quick internet search, that's often where the inquiry will end. We need to help and encourage our next generation of workers to develop an intentional focus on work habits, career growth, and creating a culture that encourages "safe dialogue," as you will read in this issue (see Perspective article, page 12).

We desperately need future engineers to step in now and become involved. They will bring new ideas, drive innovative approaches, and generate new energy. If they don't understand the importance of this, or the positive impact we have made and continue to make in the industry, they will remain unengaged and uninvolved, and our existence as engineering solution providers will cease.

Fortunately, there is excitement on the horizon. We eagerly await the arrival of the collaborative launch (by FHWA, Texas Department of Transportation, and the Cockrell School of Engineering) of the Concrete Bridge Engineering Institute (CBEI) at the University of Texas at Austin in the near future. This will no doubt energize concrete bridge engineers in the beginning stages of their careers and provide a direct and positive service to the entire concrete bridge community.

In addition to the CBEI coming online, NCBC is aligning with new knowledge-delivery systems to enhance processes for professional development hours, technical institute–based quality and personal competencies, and immersive, focused, hands-on training.

I want to thank you all for the support you've given me during these past several years at NCBC and for the support you'll undoubtedly give Gregg going forward. We'd both like to ask you to consider encouraging younger engineers to get actively involved in our organizations. They don't know what they don't know, and who knows, they might just get motivated and develop a new delivery technique or system—and you will have facilitated this achievement.

Pick a nonprofit that benefits the concrete community holistically and get involved.

Happy New Year!

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Dr. Oguzhan Bayrak is a professor at the University of Texas at Austin and was inducted into the university's Academy of Distinguished Teachers in 2014.

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CONCRETE CALENDAR FOR WINTER 2022

The events, dates, and locations listed were accurate at the time of publication but may change as local guidelines for gatherings continue to evolve. Please check the website of the sponsoring organization.

January 9–13, 2022
Transportation Research Board Annual Meeting
Walter E. Washington Convention Center
Washington, D.C.

January 18–20, 2022
World of Concrete
Las Vegas Convention Center
Las Vegas, Nev.

February 21–26, 2022
PTI Certification Training: All Levels
Sonesta Atlanta Airport North
Atlanta, Ga.

March 1–5, 2022
PCI Convention at The Precast Show
Kansas City Convention Center
Kansas City, Mo.

March 14–19, 2022
PTI Certification Training: All Levels
Doubletree DFW Airport North
Dallas, Tex.

March 21-22, 2022
ASBI Construction Practices for Segmental Concrete Bridges Seminar
Marriott Seattle Airport
Seattle, Wash.

March 27–31, 2022
ACI Spring Conference
Caribe Royale Orlando
Orlando, Fla.

April 6-8, 2022
Design-Build for Transportation & Aviation Conference
Orlando, FL

April 24–27, 2022
PTI Convention
Hilton La Jolla Torrey Pines
La Jolla, Calif.

May 2–7, 2022
PTI Certification Training: All Levels
Westin Baltimore Washington – BWI
Baltimore, Md.

June 20–23, 2022
AASHTO Committee on Bridges and Structures Annual Meeting
Pittsburgh, Pa.

July 17–20, 2022
International Bridge Conference
David L. Lawrence Convention Center
Pittsburgh, Pa.

August 2022
AASHTO Committee on Materials and Pavements Annual Meeting
Miami, Fla.

September 21–23, 2022
PCI Committee Days
Loews Chicago O'Hare Hotel
Rosemont, Ill.

October 4–7, 2022
PTI Committee Days
JW Marriott Cancun Resort & Spa
Cancun, Mexico

October 23–27, 2022
ACI Fall Convention
Hyatt Regency Dallas
Dallas, Tex.

October 31–November 2, 2022
ASBI Annual Convention and Committee Meetings
Hyatt Regency
Austin, Tex.

December 7–9, 2022
International ABC Conference
Miami, Fla.

EDITOR'S NOTE

NCBC

In follow-up to this issue's Editorial on pages 2 and 3, you can learn more about the National Concrete Bridge Council (NCBC) at https://nationalconcretebridge.org. Additional information can also be found at the Concrete Bridge Views website at www.concretebridgeviews.com

FOCUS

Contractor Paves the Way for Future Generations

Family-owned C. W. Matthews Contracting Co. Inc. celebrates 75 years as a prominent heavy civil contractor in the Southeast

by Monica Schultes

When a fire erupted beneath the heavily traveled Interstate 85 (I-85) through Atlanta, Ga., and several spans along the viaduct collapsed on March 30, 2017, C. W. Matthews Contracting Co. Inc. (CWM) stepped up with all hands on deck. Within minutes, CWM was communicating with the Georgia Department of Transportation (GDOT), and within hours, the contractor was on the job and collaborating on how to restore the bridge safely and quickly. CWM and GDOT had previous experience working together in an emergency.

Bridge engineers redesigned the spans to replace the original AASHTO Type V girders, whose forms were unavailable in sufficient quantities, with sixty-one 63-in.-deep bulb-tee beams. The project required a custom design because the horizontal curve of I-85 passing over Piedmont Road created bridge spans in a trapezoidal shape in each direction. Using the existing bridge foundations jump-started the work. Because the collapse required closing the affected stretch of highway, work-zone traffic control was unnecessary.

Except for a brief period during a thunderstorm, work never stopped. CWM crews pulled 12-hour shifts, 7 days a week, totaling 41,781 work hours over only 42 calendar days. Two construction cameras were also on site: one streamed live, high-definition video and a second continuously captured high-resolution still images.

CWM had used construction cameras on previous projects. On the I-85 rebuild, the real-time, remote monitoring enabled the project team to use their mobile devices to get up to speed before each shift so they could arrive at the jobsite with a plan.

The setting of the last beam in what was a marathon emergency reconstruction effort to restore traffic to six spans of Interstate 85 through Atlanta, Ga., in just six weeks following a massive fire beneath the bridge on March 30, 2017. All Photos: C. W. Matthews Contracting Co. Inc.

Vice president of structures Adam Grist relied on the cameras to avoid delays. "If we were expecting a delivery by 8 p.m., I could verify that it happened," says Grist. On a job where every second counted, the cameras made a difference. Everyone was able to see what was going on all the time.

The bridge repair involved six spans and was staged in a stair-step fashion. As soon as the crews installed or rehabilitated columns for a bent, they were able to cap it and move on in sequential order to complete each section of the bridge, recalls Grist.

The rapid rebuild could be completed in just six weeks because of the close collaboration between GDOT and CWM. (For more details on the I-85 emergency bridge replacement, see the Project article in the Fall 2017 issue of *ASPIRE*®.)

Warp Speed

The ability to coordinate and complete projects at warp speed is a trademark of CWM. Grist says that project schedules today are more aggressive than ever before. Seeking to minimize the inconvenience of construction on the public, "owners want to get things done as fast as possible."

"Owners want to get things done as fast as possible."

However, accelerated projects demand an extreme amount of resources in a short amount of time. "We gear up for these fast-track projects, but when they are completed, we have to rebalance our workload," Grist says. "In addition, the sheer amount of hours these types of projects command raises concerns about safety and employee burnout. With all the accelerated projects, the amount of work being performed on nights and weekends has increased considerably. Atlanta is no different than other highly populated metro areas where you have thousands of vehicles per day on the roads and bridges."

Talent Scout

As the construction industry scrambles to supplement its aging workforce with young talent, companies must make creative efforts to reach potential employees. CWM takes a proactive approach to finding, attracting, and keeping new employees. "Construction used to be a profession with unlimited employee resources," recalls Grist. "Now it is much harder to recruit." Like many construction firms, CWM has found that its biggest challenge is determining how to develop, train, and retain the next wave of skilled craft and supervisory employees. CWM is also cognizant of the need to transfer decades of knowledge and experience from the employees who are poised to retire to the next generation.

In the last five years, CWM has been actively seeking individuals who want to work in construction. In a new initiative, a former high school teacher visits technical and high schools to encourage students to consider a career with CWM.

"Not everyone has college in their future," says Grist. "By partnering with schools in Georgia, we demonstrate our support for construction management training and present the myriad opportunities in both our company and the industry. We have many examples of employees who started as laborers and advanced to upper management positions." To illustrate their enthusiasm for bringing on new hires as well as to generate some excitement after drafting them onto the CWM team, the firm has begun a "signing day," complete with team jerseys and photo ops.

Employees are also attracted by the fact that much of the company's work is in Georgia. Based in Marietta, CWM is positioned to serve the Atlanta area, which is the ninth largest U.S. metropolitan area and one of the fastest growing regions in the United States.

"I think that being local is a benefit to our company," explains Grist. "Most of the time, our crews will be able to return home to their families. Their location allows them to work within a 200-mile radius from their Marietta base of operations. That helps us to retain employees."

One project close to home was the Encore Parkway Bridge replacement in Alpharetta, Ga., constructed in 2015–2016. The $14.6 million project transformed a local cut-through into an east-west connector. The existing bridge was replaced by a wider structure with dedicated bike lanes, sidewalks, and a landscaped median. The new bridge is 116 ft wide with two 150-ft spans over State Route 400. Each span has 18 prestressed concrete 74-in. bulb-tee beams.

As a catalyst for economic development, the project included unique aesthetic enhancements. A special formliner was used on the bridge and walls to emulate natural stone. All of the concrete was stained on site with a multicolor stain.

The Encore Parkway Bridge replacement in Alpharetta, Ga., improved traffic flow and access across State Route 400. The new structure, which features stained concrete with a formliner finish that emulates natural stone, serves as a gateway to a newly developed commercial corridor.

Exceed Expectations

CWM fosters a good working environment for employees and values its long-standing relationship with GDOT. "We strive to maintain our partnership with them on all of our projects, and that collaborative effort makes it easier when a crisis happens," says Grist.

"We strive to maintain our partnership with them [GDOT] on all of our projects, and that collaborative effort makes it easier when a crisis happens."

For example, when the 2017 fire under I-85 gridlocked Atlanta, GDOT and CWM "chose to proceed without a finalized contract," Grist notes. "We relied on our relationship with the owners, and they came through." Time was of the essence, and cutting through the red tape allowed work to start as quickly as possible. GDOT was also able to be more efficient and expedited reviews, enabling CWM to work continuously without delays.

C. W. Matthews Contracting Co. Inc. sets a precast, prestressed concrete girder for the Interstate 75/Interstate 24 Interchange project in Tennessee. Several nighttime roadway closures were required for setting the girders at this and other overpasses on the project.

"Since the emergency repairs, we have devised schedule scenarios to rotate our crews," explains Grist. The I-85 project required a 24/7 effort, but CWM understood that people cannot work 40 days straight. "Now we schedule breaks for employees to have sufficient rest."

Railroad Crossing

Another notable partnership between CWM and GDOT was the project to replace the 81-year-old Greenville Street Bridge in LaGrange, Ga., which had been closed to vehicular traffic for two years before construction started in 2018. One of the many challenges facing the project team was how to work proximate to the two sets of railroad tracks without interrupting rail traffic.

Excavation for the foundations came within 15 ft of the tracks, and vertical clearance was also restricted over the tracks. Collaboration between CWM and GDOT was necessary to overcome the constructability issues. CWM offered a value-engineering proposal that resulted in the addition of two straddle bents for significant cost savings, with no adverse effect on the construction schedule.

Design-Build

GDOT has been increasing the number of design-build projects it has under contract. "We like the flexibility and creative approach design-build fosters; however, that does push more risk to the contractor," says Grist. With the understanding of the risks and rewards and the strong team of people and equipment, CWM thrives in that environment. "We just completed our first design-build project in Tennessee. We like the challenge, have the right people, and can plan for those contingencies," Grist says.

The Tennessee Department of Transportation (TDOT) contracted with CWM on the first phase of the Interstate 75/Interstate 24 interchange modification in Chattanooga. Completed in August 2021, the $132.6 million project included 11 bridges and other roadway improvements. TDOT used design-build to expedite project delivery and streamline design processes.

CWM prefers design-build over public-private partnership (P3) projects. "We are a big family-owned company, but we are not a national mega contractor," says Grist. "We do not typically pursue P3 projects as prime contractor due to the associated finance, risk, and maintenance aspects."

Always looking for innovative approaches in concert with GDOT, CWM often looks to precast concrete to help accelerate project schedules in a region where a large percentage of the bridges are concrete. Innovation will

The 426-ft-long Greenville Street Bridge in LaGrange, Ga., uses two complex intermediate straddle bents to pass over two heavily used railroad tracks.

In August 2021, C. W. Matthews Contracting Co. Inc. finished the first phase of the Interstate 75/Interstate 24 interchange modification in Chattanooga, Tenn., on time and on budget. The $132.6 million design-build project included 11 bridges, 17 retaining walls, and a noise wall.

During the 2018 Courtland Street Bridge project in Atlanta, Ga., replacing the structure in a tight urban environment created numerous constructability challenges. C. W. Matthews Contracting Co. Inc. collaborated with the Georgia Department of Transportation and Michael Baker International to ensure that the project could be executed quickly and with minimal impact to adjacent Georgia State University, which remained in operation during the project.

continue to be important in the future. Using the proceeds from a 2015 gas tax increase, GDOT plans an expansion of the region's network of toll lanes, new highway interchanges, and new bridges on "the Perimeter"—the Interstate 285 loop that encircles Atlanta.

Express Lanes

A priority for GDOT is reducing the impact of construction on both the local community and the traveling public. This goal was evident when CWM replaced the Courtland Street Bridge in downtown Atlanta in 2018. Originally scheduled to take 18 months, the $21 million project used design-build and accelerated bridge construction (ABC) methods to replace the original 111-year-old bridge over Decatur Street, public transit, and freight rail lines in just over 5 months.

According to Grist, the CWM team used innovative construction methods, all while protecting access through the work zone to Georgia State University buildings. He cited the installation of new foundations beneath the existing bridge before the road was closed as helping to meet the aggressive schedule. (See the Fall 2019 issue of *ASPIRE* for more on the Courtland Street project.)

CWM was also up against the clock for the 2019 Blackhall Road Bridge replacement project in Jonesboro, Ga. CWM used ABC methods to replace the Rum Creek crossing to reduce the project's impact on the local community. To meet the mandate for a less-than-60-day closure, the team turned to decked beam modules composed of prestressed concrete bulb-tee girders with decks cast in laydown yards at the project site. The modules were installed and then connected with ultra-high-performance concrete deck closure joints. (For more on the Blackhall Road Bridge replacement, see the Winter 2021 issue of *ASPIRE*.)

CWM's track record of quick response times, continuous communication, and using innovative technology has set a high bar for future projects. With more concrete bridges planned for the Atlanta network, CWM is poised to make a lasting imprint on the region.

On the 2019 Blackhall Road Bridge replacement project, casting the bridge deck on prestressed concrete bulb-tee girders at on-site laydown yards helped eliminate shipping-weight limitations and profile management issues and also accelerated the schedule. The first project in Georgia to use this hybrid concept, the bridge was reopened to traffic after only a 60-day closure.

On the 2018 Courtland Street project in Atlanta, Ga., prestressed concrete beams were used to span the Metropolitan Atlanta Rapid Transit Authority and CSX railroad tracks. The replacement structure was built in the same footprint as the old bridge.

Family History

C. W. Matthews Contracting Co. Inc. (CWM) is a family-owned, fourth-generation, heavy civil construction company based in Marietta, Ga. It started 75 years ago as a small grading company with a focus on asphalt and paving and has since expanded from those humble beginnings to include storm drain installation, concrete flatwork, bridges, retaining walls, and project management.

The contracting company has grown along with the region and has made several strategic acquisitions. The 2006 acquisition of APAC's Atlanta, Ga., operations helped CWM enlarge its bridge division. More recently, in May 2021, CWM acquired the Southeast operations of McCarthy Construction, which significantly increased CWM's capacity to produce and install concrete pavement. These acquisitions have greatly expanded the territory in which CWM supplies products and services and entrenched them in heavy civil construction.

Unlike publicly owned companies, the Matthews family leadership allows CWM to be flexible and employee oriented. The family believes the company's people and equipment are its greatest assets. They continue to be 100% invested in the construction industry and their own future.

The business was well positioned to weather the uncertainties of 2020. Thanks to a robust and diverse backlog, CWM continued to thrive during the COVID-19 pandemic and is prepared to build toward the future.

Road Map to Carbon Neutrality for Concrete Materials

by Richard Bohan, Portland Cement Association

Greenhouse gases and climate change affect all aspects of society. The construction materials industry is no exception, with a persistent focus on concrete and cement in particular. Design professionals often conflate the embodied carbon of materials with the environmental performance of building systems. This mistakenly neglects the role of life-cycle analysis (LCA) and fails to integrate the overall impact of selecting building materials to best address climate change. The Portland Cement Association's recently released *Road Map to Carbon Neutrality*[1] addresses this confusion by adopting a value-chain approach.

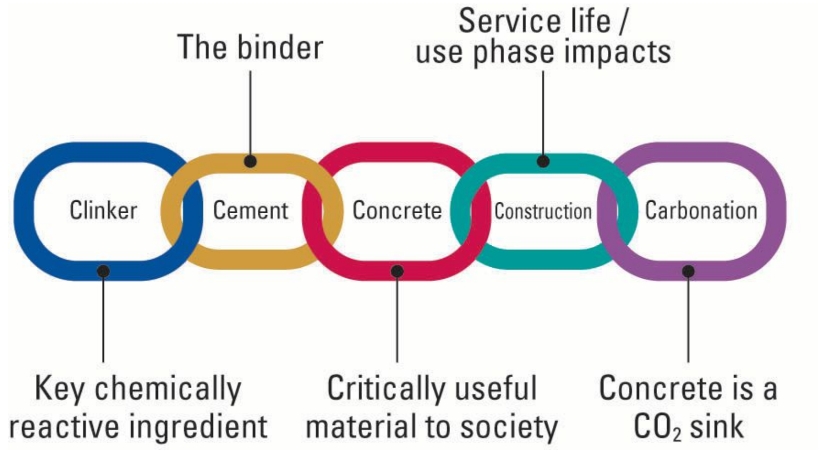
This road map to carbon neutrality encompasses the entire value chain of cement and concrete: clinker, cement, concrete, construction, and the use of concrete as a carbon sink. This approach recognizes that each link in the chain has a specific role to play in addressing the reduction or avoidance of greenhouse gases and that no individual link should be considered in isolation.

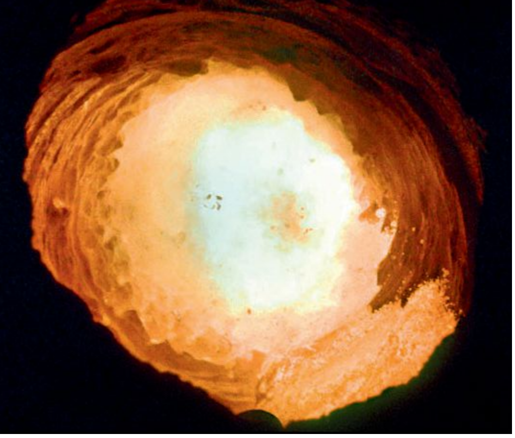
Clinker is the first step in the value chain. Clinker is an intermediate product within the cement manufacturing process and represents the initial contribution to the carbon dioxide (CO_2) footprint of concrete structures. The production of clinker requires the decarbonation of limestone as a precursor to the formation of calcium silicates and other phases. Decarbonation requires material temperatures approaching 2800°F (1500°C), which are achieved through fuel combustion. Slightly less than 40% of the CO_2 released in the production of clinker is generated through fuel combustion, while slightly more than 60% of the CO_2 released is the result of the decarbonation of calcium carbonate ($CaCO_3$). These two sources of CO_2 can be reduced by increasing the proportion of decarbonated raw materials and transitioning from traditional fossil fuels to lower-carbon fuels, alternative fuels, and transformative fuels such as hydrogen. Longer-term solutions will require carbon-capture technologies such as solvents, sorbents, and membranes, along with less-traditional capture technologies such as oxy-calcination, direct separation calcination, calcium or carbonate looping, and algae capture.

The reduction of CO_2 in the clinker production process can be further leveraged within the cement portion of the value chain, primarily through the use of nonclinker ingredients such as limestone and supplementary cementitious materials (SCMs). Portland-limestone cements Type IL, as specified by ASTM C595, *Standard Specification for Blended Hydraulic Cements,*[2] or AASHTO M 240, *Standard Specification for Blended Hydraulic Cement*,[3] provide a great example of using technology to reduce CO_2 emissions. In these cements, the amount of clinker is reduced, and within proper limits, they provide concrete strength and durability that is comparable to unblended cements. Transitioning from prescriptive-based cement specifications to performance-based cement specifications provides further opportunities to either reduce or avoid CO_2 emissions.

Focusing solely on clinker or cement overlooks the influence that concrete mixing, manufacturing, and construction practices have on the reduction and avoidance of greenhouse gas emissions. For example, concrete manufacturing can be transitioned to renewable electricity, and the transportation of concrete and concrete products can be transitioned to zero-emission vehicles.

The value chain of cement and concrete. All Photos and Figures: Reprinted from Wilson, M. L., and P. D. Tennis. 2021. *Design and Control of Concrete Mixtures*, 17th ed. Skokie, IL: Portland Cement Association.



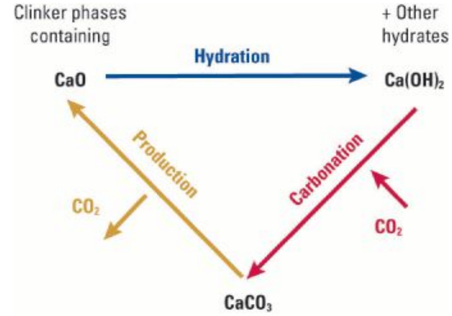


The interior of a rotary cement kiln. More than 60% of the CO_2 produced during cement manufacturing results from the calcination process whereas just under 40% results from the combustion required to reach material temperatures of approximately 2800°F (1500°C).

However, the single greatest opportunity for CO_2 reductions in concrete as a material remains with mixture optimization. Concrete mixtures can be optimized by increasing the use of SCMs and using machine-learning algorithms and other methods of artificial intelligence to discover the optimal mixture proportions for specific applications and to identify the optimal sequencing, scheduling, and delivery of concrete and concrete products. Optimized concrete mixtures can provide the best strength and durability performance and the most sustainable performance for specific applications. Quality assurance and acceptance testing of fresh concrete can also be optimized to provide better performance with less variability.

The use phase of a building accounts for 88% to 98% of the life-cycle environmental impact. Research by the Massachusetts Institute of Technology indicates that using concrete lowers the use-phase global-warming potential of a structure by up to 10% and lowers the life-cycle global-warming potential impacts by up to 8% compared with buildings that are not concrete.[4] By using LCA, integrated design principles, and performance-based specifications for construction materials, design professionals can optimize performance and reduce the embodied carbon, not just through lower-carbon cement and concrete mixtures but also through increased energy and operational efficiency, reduced maintenance and replacement, and an extended service life. The CO_2 associated with construction can be further reduced or avoided through innovative construction techniques such as additive manufacturing, a zero-waste construction site, advanced sequencing and scheduling, zero-emission deliveries, and zero-emission material-handling equipment. It should be noted that a cradle-to-gate LCA, which considers the life cycle of a product until it is ready to leave the production facility and be delivered to the construction site, does not encompass the complete impacts of a cradle-to-grave LCA or functional unit perspective. A cradle-to-gate LCA looks at an individual product such as a cubic yard of concrete, whereas a cradle-to-grave LCA looks at how the concrete is ultimately used and how the structure performs over its service life and decommissioning.

The final step in the value chain is the use of concrete as a carbon sink. Concrete absorbs CO_2 throughout its entire life through a process called carbonation. Air contains about 0.04% or 400 ppm of CO_2. That CO_2 naturally diffuses into concrete and reacts with the calcium hydroxide ($Ca[OH]_2$, a product of the cement hydration reaction) to form calcium carbonate ($CaCO_3$). The amount of CO_2 absorbed by concrete is limited to the amount released by calcination during clinker manufacture and the use of SCMs in concrete. The rate at which it is absorbed depends primarily on the concrete surface area exposed to the atmosphere, the amounts of water and moisture available, and the length of exposure. Various models using the compressive strength of the concrete, the type of structure, the type of exposure (exposed to rain or sheltered, indoor or outdoor, with or without cover, below or above ground) have been developed to calculate the degree of carbonation. Current estimates indicate that approximately 10% of the CO_2 generated during the manufacture of cement and concrete can ultimately be absorbed over the life of a concrete structure. Carbonation of good-quality concrete is acceptable, provided it does not reach the reinforcing steel. Ideally, the service life of the structure will be reached long before the carbonation reaches reinforcing steel. Carbonation of poor-quality concrete is not advocated because an increased level of permeability will allow the carbonation to reach the reinforcing steel while the structure is still in use. After the concrete structure has been demolished, the exponential increase in the surface area of the concrete allows a corresponding increase in the rate of carbonation.



The calcination–hydration–carbonation relationship. The carbonation reaction, concrete absorbing carbon dioxide to form calcium carbonate ($CaCO_3$), is the opposite of the calcination reaction, where $CaCO_3$ is transformed into calcium oxide (CaO) prior to the complex chemical reactions that form clinker and that are ultimately used to produce portland cement.

The value-chain and LCA approaches both recognize that concrete provides a valuable solution that balances society's need for a sustainable and resilient built environment while simultaneously addressing the urgent need to reduce greenhouse gases. Thus, these approaches validate the adage, "The whole is better than the sum of its parts."

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PERSPECTIVE

Psychological Safety: The Secret Behind Highly Effective Teams

by Elaine (Lainey) Lien, ReVive Careers

in·vis·i·ble dis·a·bil·i·ty: noun

According to the Invisible Disabilities Association, an invisible disability is, in simple terms, "a physical, mental, or neurological condition that is not visible from the outside, yet can limit or challenge a person's movements, senses, or activities."[1] Symptoms of the condition are invisible, which can lead to misunderstandings, false perceptions, and judgments.

As an executive, leadership development, and business coach (and someone who lives with a constant pain in the neck—no, it is not my husband), I began thinking about how organizations are like humans who suffer with chronic conditions such as invisible disabilities.

Like humans, organizations are living, breathing organisms that can experience invisible disabilities of their own. A culture of low psychological safety is a chronic condition and a type of invisible disability within an organization. Typically, this is localized at the team level, where it can be referred to as a *team invisible disability*. Although a team invisible disability may be localized, the effects can be felt throughout an entire organization, whether large or small, and across all industries, including engineering organizations.

The most common symptoms in teams with low psychological safety are silence and poor communication. These problematic symptoms are debilitating and wreak havoc on a team's performance. Productivity, engagement, and decision-making abilities are also affected. Heightened tensions and personal attacks become more frequent. Concerns and errors are often punished or ridiculed, or they go unreported. Participation, creativity, and innovation decrease. Stress and turnover increase.

What Is Psychological Safety?

Amy C. Edmondson, professor of leadership and management at the Harvard Business School and author of the best-selling *The Fearless Organization: Creating Psychological Safety in the Workplace for Learning, Innovation, and Growth*,[2] describes psychological safety as a "shared belief held by members of a team that the team is safe for interpersonal risk-taking; one will not be punished or humiliated for speaking up with ideas, questions, concerns, or mistakes."

Through years of research to better understand what is behind the success of highly effective teams, Edmondson found interpersonal risk-taking to be a key factor. Effective teams felt encouraged, supported, and comfortable speaking up with ideas for improvement, experimenting, giving and receiving candid feedback, reporting mistakes and errors, and voicing differences of opinions.

Psychological safety is *not* about promoting a peace, love, and puppies, everyone-be-nice-to-each-other-all-of-the-time environment. Silence in terms of head bobs and agreeing to and going along with everything is neither a sustainable nor effective model. Decision-making and innovation languish in such teams.

Research has found employees are reluctant to speak up when fear and intimidation are present. Long-term effects such as stress, anxiety, burnout, and higher mortality rates are by-products of continuous exposure to volatile environments. Symptomatic teams with low psychological safety suffer from silence and poor communication, and subject their organizations to disruptive, costly, and tragic side effects.

The Cost of Ignoring Silence" to See if That Works Better

Imagine working in an environment where the fear of bringing bad news to leadership heavily outweighs sound judgment. Remember "Dieselgate," the Volkswagen scandal? A team at Volkswagen, fearing explosive backlash from leaders for not being able to produce a "clean diesel" system, decided instead to equip millions of vehicles with a "defeat device" making them appear cleaner during emissions tests. Stock prices plummeted in the days following the scandal, and by June 2020, Dieselgate had cost Volkswagen $33.3 billion.[3] Although it may be considered an extreme case, this scandal is an example of how a culture of fear and silence strongly influences behaviors, and severely affects the bottom line. This also places a company's reputation at risk.

Employees who voluntarily exit a job are typically disengaged, are burned out, or received a better offer elsewhere. According to Gallup, 51% of those who voluntarily exited their company reported that in the months leading up to their departure, no leader had approached them to discuss their satisfaction or future with the organization.[4] This avoidable mistake causes significant impact to the bottom line and may potentially harm a company's reputation, making it difficult to attract and retain top talent.

Consider the following employee turnover data:

- The annual turnover rate in the United States as of September 2021 is 25%. For the latest data, see the "Job Openings and Labor Turnover" news release from the U.S. Bureau of Labor Statistics.[5]
- Turnover and replacement costs for a 100-person company with an average salary base of $50,000 can cost that company $600,000 to $2.6 million a year.[6]

Ouch! These numbers are staggering. However, when you take into account the fact that the average replacement cost of an employee can range from one-third to two times their annual salary, the expenses add up quickly.

How to Adopt a Culture of Psychological Safety

Much of the groundwork in adopting a culture of psychological safety falls to leadership, who must develop and nurture an environment where employees feel safe to express and be themselves, and to share ideas and information without fear of embarrassment, punishment, or damaged reputation.

Use the "BE WELL" tool to help your team start developing a psychologically safe culture of their own:

- **Bring** your team together regularly for a health check. Set time aside to meet with them both individually and as a group. Celebrate wins and learn from setbacks. This step helps members feel valued and significantly impacts performance and retention.
- **Expectations** set your team up for success at the beginning of each project. Clarify the vision, mission, and goals. Prepare members for potential challenges or obstacles.
- **Welcome** constructive feedback, candor, and different points of view. The intention should always be to focus on helping team members understand their errors, improve performance, or consider how a different approach might positively affect results.
- **Encourage** ideas, brainstorming, and experimenting! Innovation happens when members feel comfortable sharing their "it's crazy, but it just might work" ideas.
- **Listen** with curiosity. Listen to understand what is working and what is not. Ask questions to elicit opinions, suggestions, and concerns.
- **Lead by example** and learn to show your human side. Leaders are fallible, too. Own your mistakes, and let others know that you know you do not know everything. Learning is an essential part of growing. You are never too old or too high up in the ranks to learn something new.

Effective communication is key to treating the symptoms of low psychological safety. Highly effective teams tend to outperform other teams in productivity, innovation, problem-solving, and decision-making. These teams also enjoy higher rates of retention and lower levels of stress.

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PERSPECTIVE

How Digital Twins Can Be Applied to Help Engineers Understand the Unexpected

by David H. Parker, Parker Intellectual Property Enterprises LLC

Introduced in 2002, the concept of digital twins is still relatively new (see Perspective articles in the Summer and Fall 2021 issues of *ASPIRE®* for an introduction to this topic). This article—which is based on a detailed explanation of a proposed digital twin architecture for a bridge that was presented at the 2020 American Society for Nondestructive Testing Annual Conference[1]—presents an example of how a digital twin could be used to better understand the in-service behavior of a structure and to possibly identify problems before they become severe.

In a recent webinar, Dan Isaacs, chief technical officer of the recently formed Digital Twin Consortium, said that if you asked 10 people to define a digital twin, you would get 10 different answers. However, one thing that is universal to all digital twin concepts is the requirement for sensor data to measure the physical structure.

Given the geometric complexity, high stiffness, and environmental conditions that affect the behavior of concrete bridges, what to measure, and how, are not simple matters.[2] Such issues fall under the metrology domain, which has been a primary interest of mine for over 40 years, and, in recent years, has led me to an interest in bridge applications. Some engineers will suggest that one useful measurement parameter for bridges is deflections, primarily because they are something that engineers intuitively understand and use as design criteria, and because anomalies are readily recognized. For example, anomalies such as disparities between the physical bridge and the digital twin, asymmetries between sides and similar spans of a bridge, unexpected deformations caused by frozen bearings, and disparities between similar bridges, as well as nonlinearities, hystereses, and historical changes, can provide valuable information.

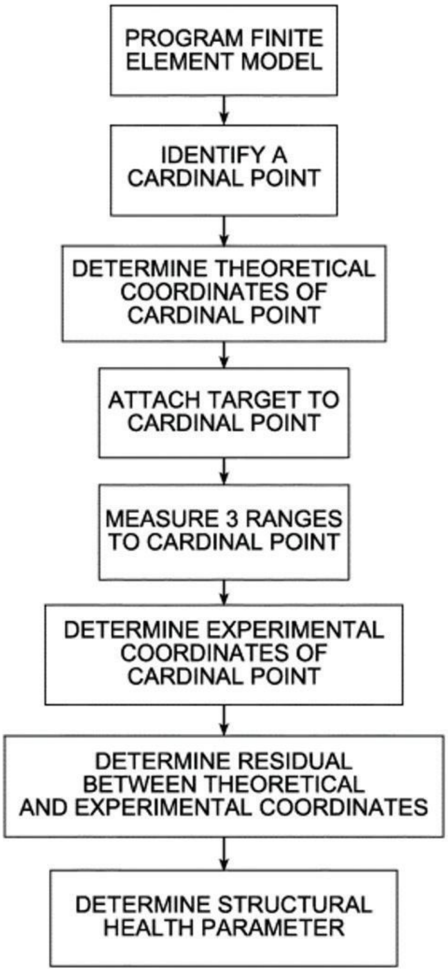
The literature on digital twins is rich with bridge proposals employing many sensors with high-speed wireless data acquisition systems. In many papers, questions about what the sensors measure, where they are located and why, and how the reams of acquired data are used, are glossed over or hand-waved to artificial intelligence or machine learning. Such an approach is anathema to experienced metrologists.

Before any measurements are taken, the uncertainties of the measurement instruments must be understood. For example, machinists sometimes work with a tape measure; however, in other cases, they may need to use a caliper or micrometer, and, in the most accurate applications, a laser interferometer may be required. Using manufacturers' specifications, statistical analysis techniques, and experience, a metrologist will know the expected uncertainty of a measurement before purchasing instruments or conducting an experiment.[3] This same rigor must be applied to digital twin instrument architectures, if they are to be useful.

Frequently, engineers have very little quantitative diagnostic information to help them understand the development of potential problems or alarming conditions. Traditional diagnostic tools such as strain gauges, inclinometers, accelerometers, and acoustic emission devices are not particularly useful for global structural assessments associated with load paths, load-carrying capacities, and diagnostics—that is, for structural health monitoring of the global structure. Modern electronic distance-measurement instruments, however, provide long-distance, noncontact, line-of-sight distance measurements with distance accuracies in the 1 part-per-million (ppm) range, comparable to strain gauges. Such high-accuracy three-dimensional (3-D) coordinate measurements, combined with a digital twin and experienced engineering insight into the selection of cardinal points to measure, can be useful in a global structural assessment.

Like total stations, the angle measurements are much less accurate than distance measurements, so care must be exercised in the measurement architecture. Some configurations may require multiple instruments in a multilateration arrangement, which only uses distances, to achieve the required accuracies. This arrangement is similar to GPS, which only measures simultaneous distances to a constellation of satellites. Instruments with such accuracies are commercially available in the form of laser trackers, which resemble the more common surveying total stations but are designed for much higher-accuracy work, such as dimensional metrology standards laboratories, machine shops, aerospace manufacturing, shipbuilding, and particle accelerators.[4] Of course, laser trackers are also very expensive—in the $80,000 neighborhood. Manufacturers' specifications comply with standards in the American Society of Mechanical Engineers' ASME B89.4.19, *Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems*,[5] which are traceable to the National Institute of Standards and Technology and, given the sophisticated customer base, are rigidly followed.

Unfortunately, the bridge community has been slow to adopt



The flowchart presents a method for using a finite element model in conjunction with experimental (remote) electronic distance meter measurements to determine structural health parameters. The most useful monitoring systems would require a partnership of bridge owners, bridge engineers, digital twin software engineers, nondestructive testing specialists, contractors, instrument manufacturers, and metrologists. Figure: David H. Parker.

this technology. However, there are many contract measurement service providers, with certified 3-D metrologists, that can provide the instruments and expertise for the metrology aspect of a project to measure cardinal points selected by bridge engineers. Readers who are not familiar with these high-accuracy instruments are encouraged to review the specifications of instruments such as those manufactured by API, FARO, and Leica and, when in-person conferences resume, attend the Coordinate Metrology Society Conference to see demonstrations of the instruments, talk with dimensional metrologists, and find measurement service providers with Level-Two-certified 3-D metrologists.

Consider the case of a complex bridge structure. It would be reasonable to require precision 3-D coordinate measurements at various stages of construction, especially if there are nonredundant elements or unique construction techniques.

For example, in an uncertainty analysis for a simple 175-ft-span bridge, I determined that two laser trackers, one located on each side of the deck in the center of the span, would be adequate to provide useful data. Given the relatively small measurement volume, a multilateration architecture would not be required in this case. However, bridges that are curved or complex would require a structure-specific uncertainty study. Maximum instrumental uncertainties in the longitudinal, transverse, and vertical directions might be 0.001, 0.005, and 0.003 in., respectively, for a simple span. Moreover, the maximum 3-D root sum square (RSS) instrumental uncertainties between adjacent measurement points would be 0.001, 0.005, and 0.003 in. times the square root of two in the longitudinal, transverse, and vertical directions, respectively. Note that the thickness of a typical sheet of printer paper is 0.004 in. It is evident that the combined measurement uncertainties will be dominated by temperature and the thermal expansion of concrete, which is around 6 ppm/°F (for example, 0.013 in./°F over 175 ft). If during a construction procedure the change in the measured length of an element is greater than the change predicted by the digital twin, and the change is well above the thermal and instrumental uncertainties, it should be investigated.

Through accurate measurements and appropriate use of digital twin applications, engineers can improve their chances of correctly evaluating what is going on before a situation becomes irreversible or even dire. By knowing the 3-D coordinates of all measurement points on the structure and comparing the movements with finite-element-method digital twin predictions, engineers can have a much better understanding of how loads are being redistributed before an element exceeds service limits or fails.

In summary, the combined use of digital twin technology and remote, yet very precise, measurements of deformations during and after construction can be a useful tool to provide accurate data for evaluation of bridge behavior, especially for unique structures.

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PERSPECTIVE

Bridge Inspection: A Monumental and Worthwhile Task

by Patrick Gallagher, Vaughn & Melton Consulting Engineers

Bridges are often viewed as the attractive, exciting part of civil engineering—and, according to this bridge engineer, they are! However, maintaining their high-standing reputation is no easy task.

While the most exciting aspect of bridge engineering is considered to be the design and construction of new bridges, we should recognize there is more to bridge engineering than that. Not every bridge rises to the level of the Golden Gate or Brooklyn Bridge. Most bridges are ordinary, unassuming, and rarely noticed after they are open to traffic. Many users do not consider the details of the designs, much less the beautiful settings these structures often pass through. Not all of the excitement and glory of bridge engineering comes through design. It takes a lot of hard work and planning to maintain these bridges, and good maintenance starts with the eyes of inspectors in the field, looking at bridges while they are in service.

The bridge engineering community designs relatively few bridges every year. Most bridges in the United States, numbering in the hundreds of thousands, are in service already. And when just one of these thousands of bridges has a problem, we immediately focus on the flaw and visualize a twisted bridge deck and gaping hole where the bridge once stood. We do not think about the intricate engineering details some midlevel engineer put into the design 60 years ago when the bridge was built. We take notice of the problem because experience has taught us that when bridges fail, disaster is close at hand.

Bridge inspection is a big deal! The safety and security of the traveling public are very dependent on how well bridges are maintained. Can you imagine how difficult your journey down the road would be if there were no bridges, or how much more traffic congestion there would be if even a few key bridges were simply taken off the map? Our cars cannot ford a river like wagons did in the pioneer days, most water crossings do not have ferries, and most of us do not rely on horses for our daily commute. We need bridges just to make it to the grocery store, and we do not even realize they are there.

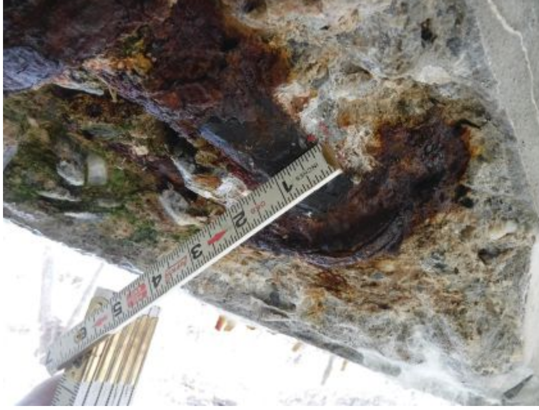
Bridge inspection was born out of rapid growth and necessity. With the construction of our interstate system starting in the 1950s, the quantity and complexity of U.S. bridges expanded rapidly. Given the volume of work to create these new bridges, maintenance budgets rarely managed to keep pace with the new infrastructure. The 1967 collapse of the Silver Bridge over the Ohio River between Ohio and West Virginia brought about the launch of our nationwide bridge inspection program. The collapse of the Mianus River Bridge on Interstate 95 in Connecticut in 1983 took the bridge inspection program to the next level, bringing about some of the components we have in our modern-day bridge inspection program. Both of these failures took the lives of many people and were the result of maintenance issues that a well-trained bridge inspector would have found if a detailed inspection program had been in place. In response to these failures, Congress directed the Federal Highway Administration to create the bridge inspection program and set the guidelines we use today.

Bridge inspection is not just about preventing collapses to save lives. It is a part of a larger program designed to assess the condition of our bridges and identify problems while they are minor and easy to repair. The data collected in bridge inspections are used to establish

Traffic control is in place to provide safe snooper access for inspectors during an interstate bridge inspection. All Photos: Vaughn & Melton.


Bridge inspectors are trained to work safely in dangerous environments and to communicate technical data in challenging situations.


Cracks and spalls being measured and documented during a bridge inspection.


Example of data being gathered on corrosion damage to a concrete element during a bridge inspection.

the condition of each and every part of a bridge so that owners, usually state departments of transportation or other local agencies, can direct their funding to address key small problems before they become big problems. The data are also used to help determine exactly how much load aging bridges can support so that heavy vehicles do not cause damage to those structures. Bridge inspection not only saves lives but also collects the data needed to ensure that our tax dollars are spent carefully and thoughtfully to maximize bridge service life at the lowest reasonable cost. Bridge inspection is about safety, maintenance, setting the right priorities, and ensuring proper loading of our bridges.

While not every bridge inspector is required to be a professional engineer, inspectors need to have intimate knowledge of how bridges work. The best bridge inspectors tend to have a background in bridge design, and most are licensed professional engineers. Bridge inspectors are required to pass a two-week training class and then get recertified every two to five years, depending on the state they work in. Often working in two-person teams, they are trained to work safely in dangerous environments, both natural and artificial, and they are prepared to communicate technical data in challenging situations. Bridge inspection is not work that is taken lightly, and states demand a high level of competence.

Recently, a bridge inspector noticed a major crack in the Interstate 40 steel bridge crossing the Mississippi River, and the bridge was immediately closed. It was later found that previous inspections had been incomplete or not properly carried out. When situations like this occur, it is easy to dismiss the credibility of the craft; however, this case is a very rare exception. Like a good bridge design, bridge inspection is not intended to be noticed. Hundreds or thousands of bridges are inspected accurately and completely every day across the country. But when concerns about inspection quality manifest themselves, they too inspire fear—and we forget to recall that good bridge inspection has served the public extremely well for decades. When bridge inspection is performed to its intended level of detail, it is truly a monumental and worthwhile task.

The next time you drive down the road, take notice of the handful of bridges you cross and recognize that maintaining them well is just as important as designing them well. Remember that good maintenance begins with bridge inspections being done by well-trained teams of technicians, engineers, and owners with your best interest in mind.

Drones can be used to augment inspection, providing perspectives not available from access equipment or in difficult-to-reach locations.

Sargent Beach Bridge

by Michael Hyzak, Texas Department of Transportation Bridge Division, and Andrew Mish, Stephen Fussnecker, and Reza Baie, Modjeski and Masters

With end and pier girder segments supported by a falsework tower, strand jacks lift the final 178-ft drop-in girder into place in the main span. After lifting, the drop-in girder was supported from the adjacent pier girders using embedded steel corbel brackets until the closure pour and post-tensioning were completed. All Photos: Modjeski and Masters.

Located on the middle of the Texas Gulf Coast is Sargent Beach, a community south of Houston on a barrier island at the end of Farm to Market Road 457. Sargent Beach has a few hundred residents and is separated from the Texas mainland by the Gulf Intracoastal Waterway (GIWW), a major waterway used primarily for barge traffic.

The original crossing carrying roadway traffic from the mainland to the island was a barge swing bridge, which was first built in the 1940s and replaced in 1974. This structure had a limited horizonal clearance of approximately 140 ft and was struck by barges about once a month, making it the second-ranked impediment to navigation on the Texas portion of the GIWW.

Project Concept and Site Constraints

In 2013, Texas Department of Transportation (TxDOT) staff in the Yoakum District and Bridge Division began collaborating on a concept that would provide a two-lane, high-level crossing of the GIWW at Sargent Beach with required 225-ft horizontal and 73-ft vertical navigation clearances. At this location, the GIWW banks are approximately 250 ft apart and the island is only about 500 ft wide.

Reinforcement being placed for a precast concrete bent cap. The column-to-cap connection, which used corrugated metal pipes to improve constructability, was a critical part of the design.

profile

GULF INTRACOASTAL WATERWAY BRIDGE / **SARGENT, TEXAS**

BRIDGE DESIGN ENGINEERS: Modjeski and Masters, Littleton, Colo., and Texas Department of Transportation, Austin

CONSTRUCTION ENGINEERS: Summit Engineering, a Modjeski and Masters Company, Littleton, Colo.

CONTRACT ENGINEERING INSPECTION: CivilCorp, Round Rock, Tex.

SERVICE LIFE ANALYSIS: Pivot Engineers, Austin, Tex.

PRIME CONTRACTOR: Austin Bridge & Road, Irving, Tex.

PRECASTER: Bexar Concrete Works, San Antonio, Tex.

POST-TENSIONING CONTRACTOR: DYWIDAG-Systems International, USA Inc., Bolingbrook, Ill.

The last 178-ft drop-in girder being erected. Each drop-in girder was cast in two segments, which were transported to the site and then spliced before erection.

The 120-ft-long, variable-depth pier girder is erected onto the pier and stabilized with a tie-down plate connection to the end girder at the falsework tower.

Project constraints included avoiding construction in the San Bernard National Wildlife Refuge to the north, which would require significant environmental coordination. In addition, the swing bridge needed to remain operational during construction, and temporary works needed to be minimized in the GIWW channel clearance zone. Structural risks at that location on the Texas coast include hurricanes and storm surges, as well as long-term exposure to a marine environment.

Extensive public involvement and conceptual designs resulted in a unique structural geometry. The main bridge navigation unit would require a 300-ft main span to keep the piers out of the water and minimize pier protection requirements and durability issues. The 300-ft span would be flanked by 195-ft end spans to gain the structural benefit of continuity over the piers. Beyond the 195-ft main-unit end spans, the approach spans on both sides minimize the footprint of the structure with a tight 150-ft centerline radius that forms a nearly 360-degree curve in a corkscrew configuration.

Main-Span Unit

The main-span unit needed a structural system geared for the marine environment and the long spans. Pretensioned and post-tensioned concrete with enhanced durability measures provided the solution. Bridges constructed using spliced pretensioned concrete girders with post-tensioning are still in their infancy in Texas, with only five TxDOT projects using this technology in the last 10 years. TxDOT has recently adopted the spliced precast, prestressed concrete girder as a standard bridge type and provides guidance in the TxDOT *Bridge Design Manual—LRFD*[1] for both I-girders and U-girders.

A span of 300 ft is relatively long for spliced girder bridges—325 ft is currently the longest in the United States—and typically requires a variable-depth section. Part of the challenge of these

The completed bridge with its three-span main-unit configuration of 195-300-195 ft, which is flanked by 150-ft-radius corkscrew approaches. The required 225-ft horizontal and 73-ft vertical navigation clearances accommodate barge traffic on the Gulf Intracoastal Waterway.

TEXAS DEPARTMENT OF TRANSPORTATION, OWNER

OTHER MATERIAL SUPPLIERS: Reinforcing steel: Harris Rebar Nufab, Dayton, Tex.; formwork: EFCO Forming/Shoring, Des Moines, Iowa, and PERI Concrete Column Forms, Fort Worth, Tex.; expansion joints: CMC Commercial Metals, Houston, Tex.; bearings: D.S. Brown, Athens, Tex.

BRIDGE DESCRIPTION: 690-ft-long, cast-in-place, prestressed concrete spliced-girder unit with 300-ft main span and 1675 ft of shallow precast, prestressed concrete slab beam approach spans in 43-ft-long spans on a 150-ft-radius centerline curve

STRUCTURAL COMPONENTS: 41 cast-in-place concrete pier columns; 39 precast concrete approach and transition bent caps; two main-span interior bent caps with precast concrete and cast-in-place concrete portions constructed in two stages; three hundred fifty-one 15-in.-deep prestressed concrete approach span beams; 8-in.-thick cast-in-place reinforced concrete deck on approach spans; 3408 ft of precast concrete spliced girders comprising the five-girder lines with 30 total individual precast concrete girder segments; 4-in.-thick precast concrete subdeck panels on spliced-girder unit with 4.5-in.-thick topping slab

BRIDGE CONSTRUCTION COST: $42.1 million

AWARD: 2021 Best Projects Award of Merit from Engineering News-Record in the Highway/Bridge category, ENR Texas-Louisiana Region.

The pier shafts are generally rectangular with rounded chamfers and an open-window configuration to minimize bulk and add aesthetic appeal.

The T-shaped cap section significantly reduced weight for shipping. The caps were cast with two corrugated metal pipe voids in the midsection that fit over the two reinforcing bar spirals projecting from the columns.

span lengths is ensuring that the piece weights, lengths, and depths are manageable for shipping and erection. TxDOT recommends piece weights be 200 kip or less for shipping and 300 kip or less for erection, and lengths should ideally be 170 ft or less. With a main-span length of 300 ft, the girder depth at the piers is typically about 14 ft.

Because most Texas precasters are based inland with no navigable water access, the pier girder segment depth posed a constraint for local producers. This depth was unlikely to allow for passage under bridges for land-based transport (12.5 ft is typically the maximum depth allowed for shipping). However, because the project was located on the GIWW and barge transport was available, TxDOT proceeded with a design using 14-ft-deep pier girder sections with a parabolic soffit for aesthetic appeal.

Because of the shipping concerns for the spliced girders, TxDOT also allowed an alternate bid for the main-span unit of a single-cell, variable-depth segmental box girder built in a balanced-cantilever manner.

Approach Spans

The challenge of the approach spans was largely geometric because of the tight radius. The superstructure selection was seen as a balancing act of span length, structure depth, number of bents, and complexity. To minimize structure depth and use techniques familiar to contractors, TxDOT opted for short-span 15-in.-deep prestressed concrete slab beams that chorded the curve, with a composite cast-in-place (CIP) concrete deck that incorporated a variable-width overhang. This shallow, smooth profile minimizes the storm surge impact on the structure.

Substructure

Single-column hammerhead pier caps were chosen for the substructure, with 37 nearly identical bents on each corkscrew approach. The reinforced concrete pier caps are 50 ft long and 4.5 ft wide with depths ranging from 4 to 8 ft accomplished with a parabolic soffit. The two main-unit bents are also 50 ft long but 6.5 ft wide with variable depths of 8 to 12 ft. The pier shafts are generally rectangular with rounded chamfers and an open-window configuration to minimize bulk and add aesthetic appeal. Multi-pile CIP concrete footings support the single columns.

Depending on the location in the bridge, corrosion-resistant reinforcement could be either hot-dipped galvanized, low-carbon/chromium steel or stainless steel; stainless steel reinforcement was required near splash zones closer to the ground.

The girder sections over the piers are 120 ft long and have variable depths of 8 to 12.5 ft to accommodate the negative moment caused by continuity while reducing girder weight.

A single crane was used to erect each pier girder within the tight site conditions. The out-of-balance moment during erection was the controlling design load for the cap-to-column connection.

The CIP concrete construction used TxDOT's high-performance concrete,[2] which includes supplementary cementitious materials to counter the risks of alkali-silica reaction and delayed ettringite formation and to also reduce permeability.

Alternate Designs

TxDOT allows post-let alternate designs for select concrete elements to provide avenues for innovation with atypical precast concrete components.[3] On this project, TxDOT recognized the replication of form of the substructure caps and provided a plan note allowing substitution of precast concrete caps—instead of the CIP concrete pier caps in the original TxDOT design—for review and approval. In addition, the superstructure plans allowed for contractor alternates for the spliced-girder unit considering the range of cross-section forms and construction or design techniques that might surmount the transport limitations, as well as the segmental concrete box-girder alternate. The Sargent Beach Bridge was let to contract in July 2017 with nine bidders. Of the nine bidders, the six lowest bidders selected the spliced-girder option.

Alternate for the Spliced-Girder Unit

Before project letting, a precaster worked with an engineering firm to investigate an alternate spliced-girder design. After the project was awarded, the two parties worked with the general contractor to present the alternate design concept to TxDOT. The intent was to reduce the girder weights to within the handling and shipping weight limits of the precaster's equipment. All of the pier locations and span lengths from the original TxDOT design were maintained.

Considering the shipping route and available equipment, the maximum shipping weight for the girder sections was determined to be 280 kip. To maintain girder weights within this limit, the girders were designed with a cross section based on the TxDOT "Long Span Precast I-Girder" standards[4] so that the forms could be used on future projects that incorporate the same standards. The girder sections over the piers are 120 ft long and have variable depths of 96 to 150 in. to accommodate the negative moment caused by continuity while reducing girder weight. The bottom-flange thickness is tapered from the pier to the splice location at the end of the pier segment to provide a sufficient compression block over the piers. The end girders of the main-span unit are 133 ft long with a constant depth of 96 in. Owing to the structure's geometry, the main-span drop-in girder is 178 ft long. To maintain the established girder weight limit, each drop-in girder was cast in two segments and spliced on site before erection.

Because the navigation channel had to remain operational during construction, temporary falsework supports in the channel were not allowed. Therefore, the main-span drop-in girder had to be supported by the pier girders during erection using specific erection sequencing and staged PT details for the alternate design. A detailed analysis was performed for all stages of construction to ensure that the temporary stresses in

AESTHETICS COMMENTARY

by Frederick Gottemoeller

Simple, direct design solutions always have immense appeal because observers of the structure can immediately understand both the challenges and the solutions. Visually, the Sargent Beach Bridge is about as simple and direct as it gets.

Neither the island nor the mainland has room for linear approach viaducts? Fine, we'll bend the viaducts into spiraled corkscrews. The main span is too long for standard girders? Fine, we'll splice in deeper, tapered sections over the piers to accommodate the greater forces there. The pier caps are too heavy to ship? Fine, we'll carve away all of the unnecessary concrete and create an elegant shape in the process. The pier shafts look too massive? Fine, we'll pierce them with a wide vertical slot.

As I've often pointed out, attractive bridges use their shapes to illustrate how they work: they are thick where the forces are the greatest and thin everywhere else. People intuitively understand the reasons for these shapes, and this understanding results in a positive feeling of engagement and satisfaction. Here, the tapered haunches of the main span, the tapered arms of the pier caps, and even the vertical slots in the pier shafts reflect this differentiation of forces, making the bridge elegant as well as efficient and economical.

In the flat, Gulf-side landscape, I can imagine that this structure is the tallest thing around, making it a signature landmark for the community and its visitors. I predict that Sargent Beach residents are going to be proud of this structure for a long time to come.

One of the 280-kip, variable-depth pier girders arrives on the jobsite. The girders were shipped over 210 miles to the jobsite with specialty trucking equipment.

the girders were within acceptable limits and that allowed erection elevations to be calculated at different phases. The erection sequence of the three-span main unit is as follows:

- End girder segments in spans 1 and 3 were erected onto the approach pier and falsework.
- Next, the pier girder segments were erected onto the main-span piers and the same falsework, with a tie plate connection to the end girder segment for stability. These two girder segments were then spliced by placing concrete in the closure joint and tensioning the first-stage (top) post-tensioning tendon, which used fifteen 0.6-in.-diameter strands.
- Once this procedure was performed on both sides of the channel, drop-in girders were erected and supported by the pier girders. The drop-in girders were temporarily supported using embedded steel corbels that had been cast into the segments at the splice. After the drop-in girders were erected, concrete was placed in the final splice locations and second-stage post-tensioning consisting of four full-length tendons, each with fifteen 0.6-in.-diameter strands, was tensioned.

Alternate for Precast Concrete Bent Caps

An alternate precast concrete bent cap design was also developed for the substructure. Using precast concrete minimized risk with the amount of high-performance concrete that the contractor needed to cast on site. In addition, using precast concrete bent caps shortened the schedule by allowing up to six caps to be erected per day.

The alternate design incorporated pretensioning to enhance the caps' long-term durability, which was very important given the marine environment and the desired 100-year service design life of the bridge. With the addition of pretensioning in the bent caps, the design team investigated using black carbon steel reinforcement instead of the stainless, hot-dipped galvanized, or low-carbon/chromium steel called for in the original design. The pretensioned bent caps were designed to maintain a fully compressed section under all permanent loads, eliminating the likelihood of flexural tension cracks. A service-life study for the precast concrete bent caps concluded that increasing the clear cover for the reinforcement from 3 to 3.5 in., incorporating a corrosion-inhibiting admixture into the concrete mixture, and pretensioning the cap would provide sufficient durability and corrosion resistance to meet the 100-year design life requirement while using black reinforcing bars and strands.

As with the girders, the bent caps were designed for all stages of construction. A variable-depth T-section was used as the cantilever arm of the hammerhead with a rectangular cross section over the column. Using the T-section significantly reduced weight for shipping: the approach span caps weighed 144 kip and the main-span bent caps weighed 246 kip, compared with 207 kip and 504 kip, respectively, in the original design.

The column-to-cap connection was a critical part of the alternate design, and constructability was a primary focus. The connection details were based on TxDOT standards[5] with project-specific modifications. The caps were cast with two corrugated metal pipe voids in the midsection: 21-in.-diameter voids for the approach caps and 30-in.-diameter voids for the main-span caps. Two reinforcing bar spirals projected from the top of each column, and each bent cap was erected with the corrugated voids encompassing the protruding reinforcing bar spirals from the columns. The 2- to 3-in. joint between the column and cap was filled with high-strength grout, and the corrugated voids were filled with the same concrete mixture as the column to complete the connection.

The connection was designed to account for all construction loadings; the critical load case was found to occur during girder erection. The main-span girders were erected from west to east starting with the exterior girder, creating a significant out-of-balance service moment with the first two girders erected. The precast, pretensioned concrete bent cap and its constructable, robust connection with the column had sufficient capacity for the task.

Results

On the Sargent Beach Bridge project, TxDOT's allowance for alternate design, coupled with the ingenuity of an engineer, precaster, and contractor, helped the project team successfully navigate site constraints and transportation challenges. The result was savings of materials, costs, and time.

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A Challenge of Geometry

Value-engineered shift from steel to concrete saves $19 million on a complex Interstate 20 bridge project

by Natalie McCombs, HNTB, and Micah Dew, Mississippi Department of Transportation

Aerial view of completed bridge before opening to traffic, looking west. Photo: Mississippi Department of Transportation.

The Mississippi Department of Transportation (MDOT) had deemed a heavily traveled stretch of Interstate 20 (I-20) in Jackson, Miss., to be in need of replacement. The existing structure had three steel straddle-bent cap beams that classified the bridge as fracture critical. The goal was to replace a deteriorated section of I-20 eastbound with a larger bridge at the interstate's confluence with Interstate 55 (I-55) and U.S. Route 51 (U.S. 51). Once complete, the new bridge would handle eastbound I-20 traffic.

The project's complex geometry and long, elevated spans seemed to dictate the use of steel girders for the bridge superstructure. However, such a design would be costly, so examining the budget and identifying ways to reduce costs became key discussion points early in the design process. MDOT engaged a design consultant to perform a formal value-engineering study to identify specific ways to reduce the overall project cost.

A Consequential Shift in Direction

Original preliminary designs called for a 1789-ft-long bridge consisting of three units: unit 1 with three spans, unit 2 with one span, and unit 3 with four spans (**Fig. 1**). However, the 360-ft-long span in unit 3 required rather substantial 144-in.-deep steel girders, which in turn mandated a taller overall bridge structure to achieve required vertical clearances. More specifically, designers specified steel plate girders on radial bents supported by drilled shafts and pile footings. The bridge units each consisted of welded plate girders with 80- or 144-in.-deep web plates, flange thicknesses up to 3¼ in., and multiple grades of weathering and high-performance steel.

The roadway varied in width from 60 to 72 ft. Additionally, the design of the east end of the bridge addressed the embankment stability by using a pile-supported relieving platform and reticulated micropile walls.

The steel girder component had a cumulative effect on cost, primarily due to the expense of erection and longer fabrication lead times. The initial cost estimate for the entire project was $50 million, with the bridge portion totaling $37 million.

Prestressed concrete beams are common in the state of Mississippi and are easy to fabricate and erect. The largest cost savings would come by using innovation

profile

INTERSTATE 20 EASTBOUND BRIDGE OVER INTERSTATE 55 SOUTH, INTERSTATE 20 WESTBOUND RAMP, U.S. ROUTE 51, AND CN RAILROAD / HINDS COUNTY, MISSISSIPPI

BRIDGE DESIGN ENGINEER: HNTB Corporation, Kansas City, Mo.

CONSTRUCTION ENGINEER: Huval & Associates Inc., Lafayette, La.

PRIME CONTRACTOR: Key Constructors LLC, Madison, Miss.

PRECASTER: Gulf Coast Pre-Stress Partners Ltd., Pass Christian, Miss.—a PCI-certified producer

POST-TENSIONING CONTRACTOR: Structural Technologies Inc., Fort Worth, Tex.

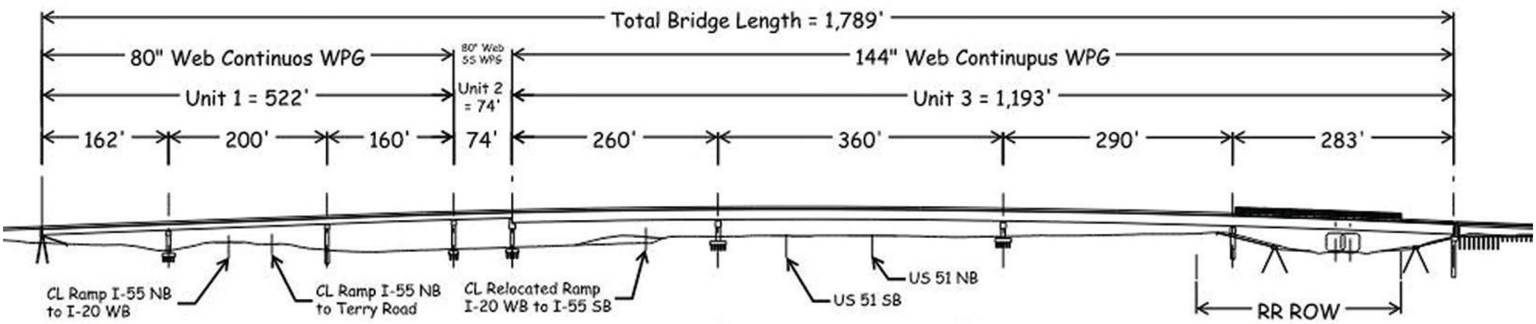


Figure 1. Original preliminary design with steel girders. Span 1 is at the west end (left). All Figures: HNTB Corporation.

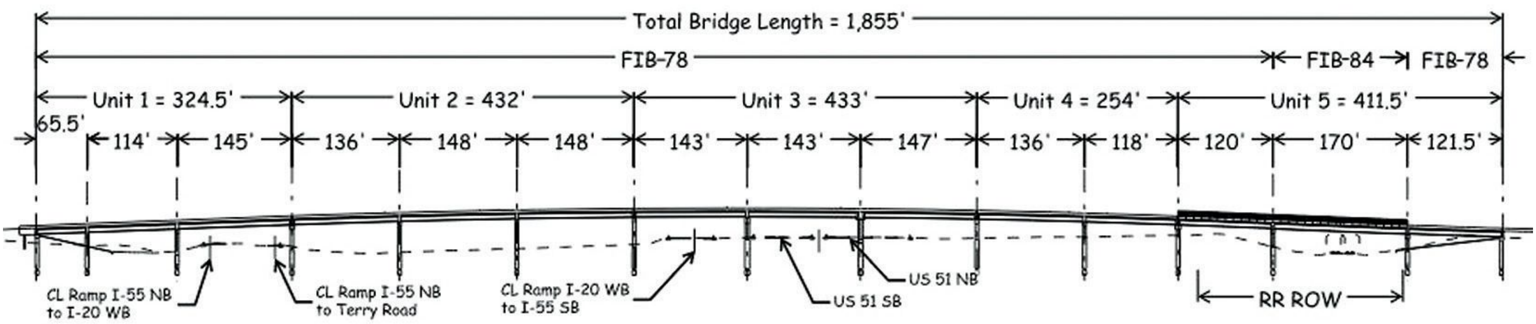


Figure 2. Value-engineered solution with prestressed concrete beams. Span 1 is at the west end (left).

Aerial view of the bridge under construction looking west toward bent 1. Prestressed concrete beams have been erected and stay-in-place deck forms and deck reinforcement have been placed. Photo: Mississippi Department of Transportation.

in bent placement and nontypical bent designs. The goal was to get the span lengths down to within prestressed concrete beam limits, which the design consultant was able to achieve. The value-engineering study revealed the following 10 items could bring the project cost within budget:

- Keep an existing I-55 southbound ramp in its existing location beneath the bridge.
- Place some foundation elements in the median of U.S. 51.
- Incorporate straddle bents where necessary.
- Incorporate drilled shafts for the entire bridge substructure.
- Skew bents to accommodate various ramps and roadways.
- Use post-tensioned inverted-tee cap beams where appropriate.
- Use precast, prestressed concrete beams.
- Innovatively reduce the length of the span over a 200-ft-wide railroad right-of-way.
- Lengthen the span on the east end of the bridge by 62 ft to avoid the need for a pile-supported relieving platform and reticulated micropile walls.
- Flatten the horizontal curve where possible.

An overhauled design with a longer 1855-ft bridge and roadway widths ranging from 60 to 72 ft was recommended. Most significantly, the bridge incorporated more, albeit shorter, spans. Apart from a 170-ft-long span over the railroad at the project's easternmost end, none of the other spans exceeded 148 ft along the centerline.

To accommodate the curved horizontal alignment and skewed substructure units, the prestressed concrete bulb-tee girders are on chords between bents and are flared with spacings varying from 9 ft to 11 ft 4 in. Of the girder spans, there are 13 spans of 78-in.-deep prestressed

MISSISSIPPI DEPARTMENT OF TRANSPORTATION, OWNER

OTHER MATERIAL SUPPLIERS: Reinforcing steel: Magnolia Steel Co. Inc., Meridian, Miss.; girder lift assistance: Barnhart Crane & Rigging, Jackson, Miss.; bearing devices: R.J. Watson Inc., Alden, N.Y.; expansion joints: Watson Bowman Acme Corp., Amherst, N.Y.; deck drainage system: C.L. Dews & Sons Foundry & Machinery Company Inc., Hattiesburg, Miss.

BRIDGE DESCRIPTION: 1855-ft-long, 5-unit, 14-span prestressed concrete Florida I-beam bridge

STRUCTURAL COMPONENTS: 12,202 ft of prestressed concrete beams with 86 FIB-78 and 7 FIB-84 beams, 8-in.-thick cast-in-place deck slab with metal stay-in-place forms and concrete continuity diaphragms supported on cast-in-place concrete multicolumn bents, two of which have post-tensioned straddle cap beams, all supported on drilled shafts

BRIDGE CONSTRUCTION COST: $19.3 million concrete Florida I-beam (FIB-78) girders and one span of 84-in.-deep prestressed concrete Florida I-beam (FIB-84) girders in the railroad right-of-way. These are the longest and deepest precast concrete girders to ever be used in the state.

The outcome of the study (**Fig. 2**) was significant and consequential, as it lowered construction costs, improved traffic management, and minimized long-term maintenance. Ultimately, approximately $19 million in project savings were identified. The as-bid construction cost for the bridge was $19.3 million.

Complex Geometry

Challenges of geometry are not uncommon on interstate bridge projects, and the I-20 project was no exception. For example, spans 1 through 10 (**Fig. 3**) are on a 1488-ft-radius horizontal curve and have a cross slope up to 9.2%, whereas spans 11 through 14 are on a tangent alignment. Additionally, much of the bridge is in a 1130-ft-long vertical curve with 3.7% grades. The width of the bridge also varied—the east end of the bridge was 60 ft wide, whereas the west end was 72 ft wide along the curve.

To make the bridge geometry work, the bents were creatively situated in roadway medians and shoulders and skewed by as much as 40 degrees to accommodate the railroad, roadways, and ramps.

Bents 8 and 9 were particularly challenging because the roadways beneath them precluded a typical multicolumn bent design. These bents were supported by only two columns to allow traffic below to pass under the cap beams. The cast-in-place concrete straddle cap beams spanned 65 ft and two stages of post-tensioning. The first stage was for the self-weight of the cap beam and the second occurred after the girders were set. Each cap beam has four tendons with thirty-seven 0.6-in.-diameter strands tensioned from only one end, with two tendons tensioned in each stage. The locations of the columns were tied to the clear zone of the roadway below. The layout required one end of the cap beam to cantilever beyond the column to support the exterior girder, resulting in a nonstandard drape of the post-tensioning tendons. The unique

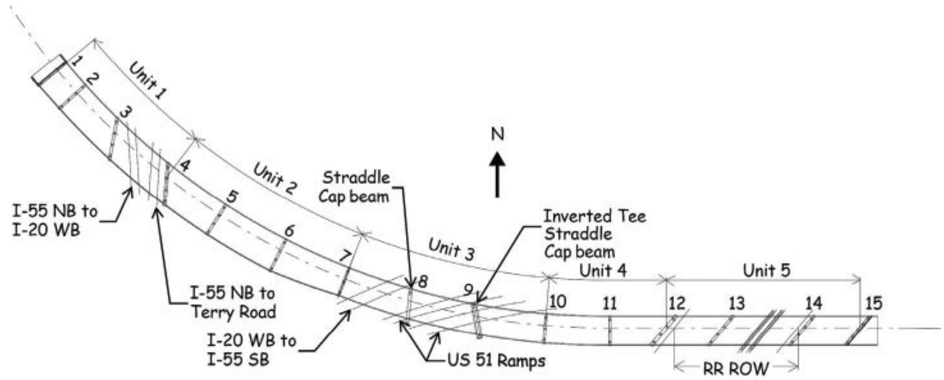
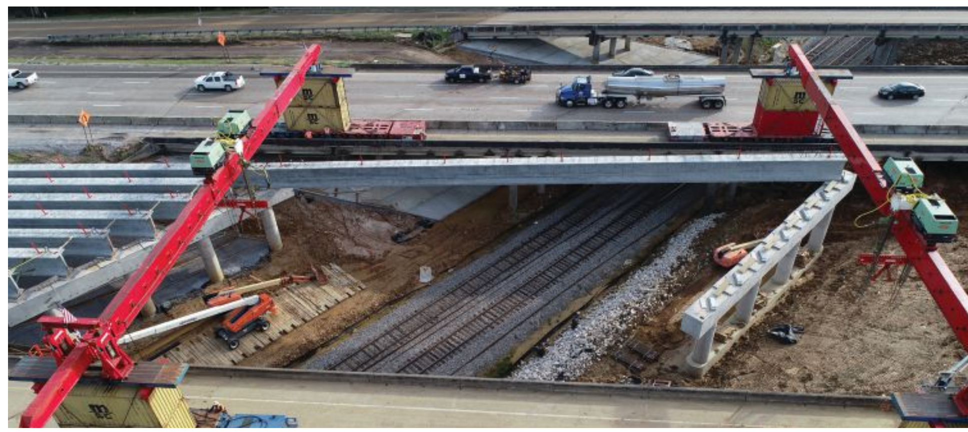


Figure 3. The schematic plan view of the structure illustrates the project's complex geometry and the challenging pier orientations. Bent numbers are shown on the figure.

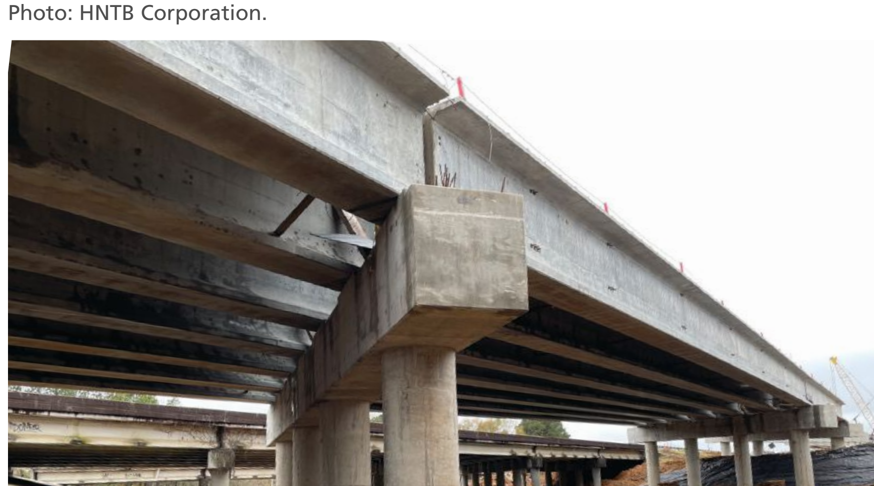


Setting the 170-ft-long, 84-in.-deep prestressed concrete Florida I-beams over the railroad tracks was a challenge. These 200,000 lb girders were erected with an innovative gantry system using self-propelled modular transporters (for details, see the related article in the Summer 2021 issue of *ASPIRE*®). Photo: Mississippi Department of Transportation.

post-tensioning and loading led to a maximum post-tensioning jacking force of 1735 kip (80% of the ultimate tensile strength of the prestressing tendon, $0.80 \times f_{pu}$), with a maximum effective post-tensioning force of 1474 kip ($0.68 \times f_{pu}$).

While most columns have a 4-ft diameter with 4.5-ft-diameter drilled shafts, the columns at straddle bents 8 and 9 are 5.5-ft in diameter and supported by 6-ft-diameter drilled shafts. Bent column heights vary from 12 to 50 ft. Column configurations are as follows: bents 2 through 6 and 12 through 14 are four-column bents; bents 7, 10, and 11 are three-column bents; bent 8 is a two-column straddle bent with a post-tensioned cap beam; and bent 9 is a two-column straddle bent with an inverted-tee post-tensioned straddle cap beam made integral with the superstructure. For bent 9, the beams were set on the corbel of the inverted-tee cap beam and then a full-depth cast-in-place concrete diaphragm was placed around the beams to make the fully integral connection.

Looking south at the installed 178-ft-long, 84-in.-deep prestressed concrete Florida I-beams crossing the railroad. These are the longest girders used in Mississippi to date. Photo: HNTB Corporation.



Bent 8 has a 65-ft-long straddle cap beam that required two stages of post-tensioning. The first stage was for the self-weight of the cap beam (already completed); in the second stage, tendons were tensioned shortly after the girders were set (not yet completed). Photo: HNTB Corporation.

Prestressed concrete girders sit on the inverted-tee straddle cap beam at bent 9 before placement of the full-depth continuity diaphragm. Each of the two straddle cap beams has four tendons with thirty-seven 0.6-in.-diameter strands that were tensioned from only one end. Photo: HNTB Corporation.

Unquestionably, prestressing in the concrete girders was integral to achieving necessary span lengths. Twenty different strand-pattern designs were needed to accommodate span lengths from 60 to 150 ft for the FIB-78 girders and the longer-span FIB-84 girders, while also achieving loading and camber criteria. Of the 14 spans, only four had girder lengths with less than 5 ft difference between the shortest and longest girders per span. For all other spans, the difference in girder lengths from shortest to longest per span varied between 5 and 55 ft.

Innovating Along the Way

On the project's eastern end, lengthening the bridge was proposed to accommodate a long-standing slope stability issue in the railroad right-of-way and to allow installation of slope stability piles and monitoring of the slopes throughout construction.

The railroad right-of-way was 200 ft measured perpendicular to the track, which then required a longer span along the alignment. As with the original design, the railroad would allow only one pier in their railroad right-of-way; also, this pier had to be a minimum of 54 ft clear from the nearest track, and there were two tracks. These criteria set the maximum span length for the entire project. This resulted in the placement of the longest concrete girders in Mississippi's history, seven of them reaching 170 ft and weighing 200,000 lb each. These large girders, as well as the girders in the two adjacent spans, were erected with an innovative gantry system using self-propelled modular transporters. For details of the system, see the Creative Concrete Construction article in the Summer 2021 issue of *ASPIRE*®.

Standard 78-in.-deep Florida I-beams typically have a maximum span length of 150 ft. To increase the span length of this section, thickening of the 4-ft-wide top flange was considered.However, this solution would have added a significant amount of weight for very little structural gain. The solution that was ultimately chosen was to simply use the FIB-84 section, which is the next larger standard size in the Florida I-beam family of sections. The 6-in. additional web depth provided the required increased structural capacity at a fraction of the additional concrete weight.

There were other creative solutions. To decrease the number of expansion joints in the curved bridge from 15 to 6, the team used full-depth diaphragms to make the girders continuous for live load. By embedding the beams into concrete diaphragms at the piers, the design (nonstandard for MDOT) closes the joint and forces water to travel down to the next expansion joint. In effect, locations where the water will drain onto the substructure are limited; this design decision will result in less long-term maintenance and more durability in the substructure.

Material specifications for major components were as follows:

- The cast-in-place, 8-in.-thick concrete slab had a 28-day concrete compressive strength of 4 ksi.
- For bents 8 and 9, the concrete in the bents and drilled shafts had a minimum 28-day concrete compressive strength of 6 ksi.
- For all other bents, concrete in the bents and drilled shafts had a minimum 28-day concrete compressive strength of 4 ksi.
- Prestressed concrete beams had a minimum concrete compressive strength at transfer of 6.5 ksi and 8.5 ksi at 28 days.
- Mild steel reinforcement was Grade 60 ASTM A615.[1]
- For pretensioning and post-tensioning, ASTM A416[2] Grade 270 0.6-in.-diameter strands were used.

Conclusion

Creative value engineering and innovative construction techniques saved MDOT $19 million on this complex project. The bridge was open to traffic July 22, 2021, with other tasks continuing through the end 2021.

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Extending the Life of Concrete Segmental Bridges

by Chris Davis, Scott Greenhaus, and Bob Sward, Structural Technologies; Craig Finley and Jerry Pfuntner, Finley Engineering Group

Concrete segmental bridges were introduced in the United States in the early 1970s and rapidly gained popularity in the 1980s. Today, there are more than 400 concrete segmental box-girder bridges in service throughout the United States, according to data from the American Segmental Bridge Institute (ASBI). A few of the first-generation bridges, which were constructed up to the mid-1990s, are showing signs of distress and need rehabilitation. This article details common causes of observed distress and how to identify them, provides an analysis overview, and discusses repair and rehabilitation methods and how the service life of these structures can be extended.

The design and construction of concrete segmental bridges in the United States have evolved over several decades, including improvements in the following areas:

- Design methodology, software, and American Association of State Highway and Transportation Officials (AASHTO) specifications to account for long-term effects and service life considerations
- Details for post-tensioning that facilitate inspection and improve corrosion protection
- Grouting procedures and grout mixtures
- Post-tensioning systems
- Concrete and reinforcement materials
- Construction methodologies
- Inspection tools and techniques to detect deterioration
- Control of life-cycle costs
- Maintenance techniques

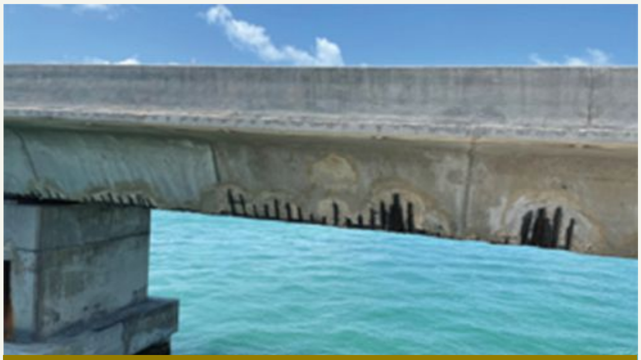
The reality has always been that segmental bridge technology is based on construction methods that have design implications. Therefore, rehabilitation of these bridges must start from this perspective as well.

Segmental Bridge Performance Challenges

Construction Issues

Construction defects can have significant impacts on the long-term service life of segmental bridges. When conditions such as misalignment of segments, damaged shear keys, and geometry control issues are identified during construction, they can be addressed during the construction phase without affecting the service life of the bridge. However, undetected deficiencies such as misplaced reinforcement, damaged epoxy coating of reinforcing bars, incomplete grouting of post-tensioning tendons, poor closure-pour construction, and voids and honeycombs inside the concrete can significantly affect a bridge's operating costs and service life. Undetected defects such as these can manifest into life-safety situations, requiring emergency repairs years after construction has been completed. The recently repaired Roosevelt Bridge in Stuart, Fla., is an example of how construction deficiencies can surface decades later and result in the need for the temporary

A precast concrete segmental bridge with a joint opening extending the full depth of the deck. The spalling is due to a lack of prestressing across the joint and issues with the top-slab dimensional proportions. Photo: Finley Engineering Group.



A precast concrete segmental bridge with loss of concrete cover and reinforcement cross-sectional area due to corrosion of reinforcement after approximately 45 years of service and exposure to a saltwater environment. Photo: Finley Engineering Group.

closure and emergency repair of a vital infrastructure corridor. In this case, the construction of the midspan closure allowed water to get into the tendons, resulting in corrosion and failure of several tendons.

Design Issues

Segmental bridge design best practices have advanced significantly over the past few decades with increased software capabilities, improved knowledge of materials, and advances in design and construction specifications. Early segmental bridges were designed with the latest technology available at the time, but design and construction experience and tools were more limited than they are today. For example, in previous eras, three-dimensional analysis software was not readily available to capture the effects of curvature and superelevation. Determination of these effects relied on the skill of the design engineer to approximate and combine these phenomena, which were not always properly captured. Previous design specifications also did not address some critical design provisions such as web principal stresses and local anchorage zone design. The cracking of the West Seattle Bridge in Washington state is a recent example of a situation where previous design specifications did not anticipate the design issues that occurred many years after the bridge was placed in service. In addition, previously used design details such as dry joints between segments and metal post-tensioning ducts have been largely eliminated from today's standard design practices. Although most older segmental bridges continue to perform well, a few may eventually face challenges from some of the past details and practices that were used in their construction.

Material Issues

The influence of material characteristics and the interaction of adjacent materials can affect the durability and service life of concrete segmental bridges. The materials and their characteristics should be carefully considered for both new construction and repairs. Implementation of a comprehensive strategy for durable concrete as part of the design and construction process may yield the largest improvement in overall durability and service life of segmental bridges. Such an approach takes into account not only the structural design parameters (for example, exposure, stress levels, concrete cover, and reinforcing steel types) but also the constituents of the concrete mixture proportions (such as aggregate quality and size, cement type, water content, and admixtures). It is not uncommon to see designs that include additional costs for epoxy-coated or stainless steel reinforcement but overlook relatively less costly enhancements to the mixture proportions that can significantly improve the overall durability and quality of concrete and extend the service life of the structure.

Grouting Improvements for Post-Tensioning Systems

Throughout the 1980s and 1990s, cement, water, and expansive admixtures were part of the standard formula for post-tensioning grouts. These grouts have proven to be susceptible to bleed water at high points and post-tensioning anchorages, resulting in voids in tendon ducts at critical locations. This situation gained attention in 2000 when several external tendons on the Mid-Bay Bridge in Okaloosa County, Fla., failed.[1] The investigation into this event, as well as others, has led to a better understanding of grout rheology, mixing, placing, and duct system detailing requirements. Subsequent improvements in the grouting process and duct systems have been developed and implemented.

In response to post-tensioning system deficiencies and the improvements required, the Post-Tensioning Institute (PTI) and ASBI worked together to develop specifications for materials, installation, and grouting of multistrand, post-tensioned tendons, as well as training and certification programs. The *Specification for Multistrand and Grouted Post-Tensioning* (PTI/ASBI M50.3-19[2]) and *Specification for Grouting of Post-Tensioned Structures* (PTI M55.1-19[3]) provide detailed product specifications

Comparison of grout column samples. The sample on the right exhibits bleed water segregation; the sample on the left is a nonbleeding, nonsegregating grout. Photo: Structural Technologies.

Post-tensioning system details and procedures, quality assessment, quality control, and technician training and certification requirements have all contributed to more successful and reliable tendon grouting. Photo: Structural Technologies.

and inspection requirements for post-tensioning systems and components such as plastic ducts and anchorages. They specify procedures and details as well as requirements for equipment, inspection, and crew training, experience, and supervision. PTI and ASBI technician and inspector certifications have become standard requirements in most project specifications. There are currently a combined total of 1700 PTI- and ASBI-certified technicians and inspectors (see the Winter 2017 and Summer 2019 issues of *ASPIRE*® for articles on improvements in post-tensioning systems).

The impact of these efforts on the quality of in-place grouted post-tensioning systems has been dramatic. When Structural Technologies/VSL inspected 10,631 post-tensioning tendons, in all types of bridges, that were grouted in the 1980s and 1990s, they discovered voids in approximately 8% of the tendons. By comparison, inspectors discovered voids in less than 0.09% of 5200 tendons inspected that were grouted between 2000 and 2009.

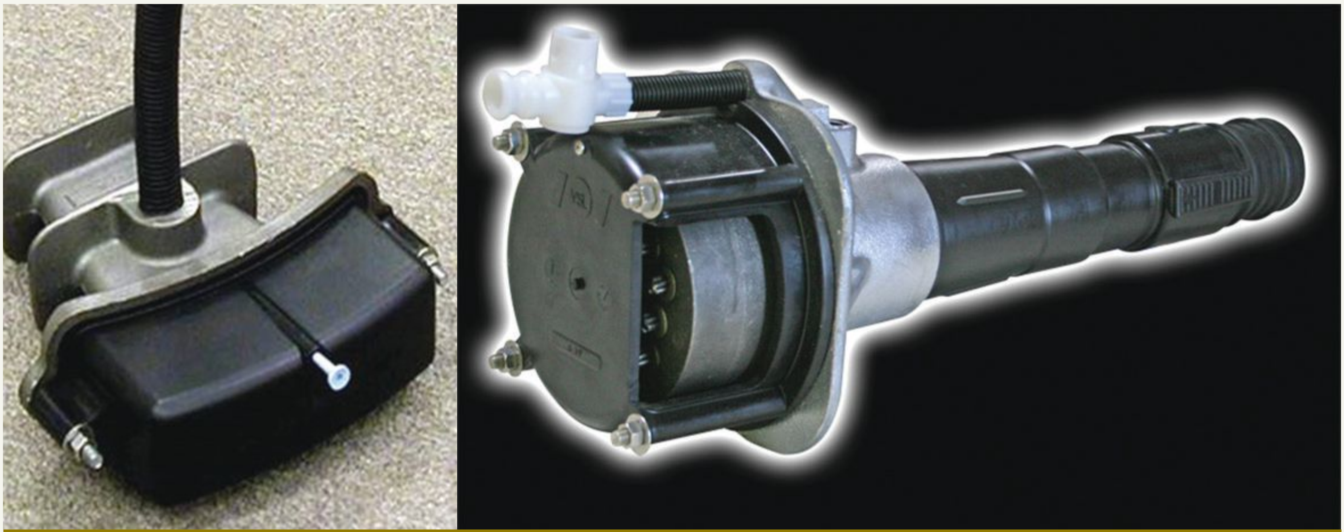
An alternative to using cementitious grouts in post-tensioning ducts is the use of wax or grease, referred to as flexible fillers, an innovation that is relatively new to the U.S. concrete bridge industry. The application of wax involves injecting heated material (approximately 270°F) into the ducts in lieu of cementitious grout. The use of flexible fillers requires special training, equipment, and modifications to standard post-tensioning systems and associated hardware for injecting the material. The unbonded nature of these tendons and the reduction in concrete cross section due to the wax-filled ducts create design implications affecting both flexure and shear.

Inspection and Investigation of Concrete and Post-Tensioning Systems

Inspection of concrete bridges is a multifaceted undertaking, requiring careful planning and execution to ensure that useful results pertinent to the assessment of the structure are obtained. The structure can be inspected through a variety of visual observations, nondestructive testing, and exploratory methods that provide information regarding the bridge system and components.

The inspection of the concrete, mild reinforcement, grout, and post-tensioning systems may entail some or all of the following methodologies.

- **Visual inspection:** Post-tensioned segmental structures, when properly designed and constructed, typically have either no cracks or a few isolated, narrow cracks. Any widespread or severe cracking may indicate a significant problem within the structure. Crack locations and patterns should be documented throughout the structure. Cracking may reduce the durability of the concrete.



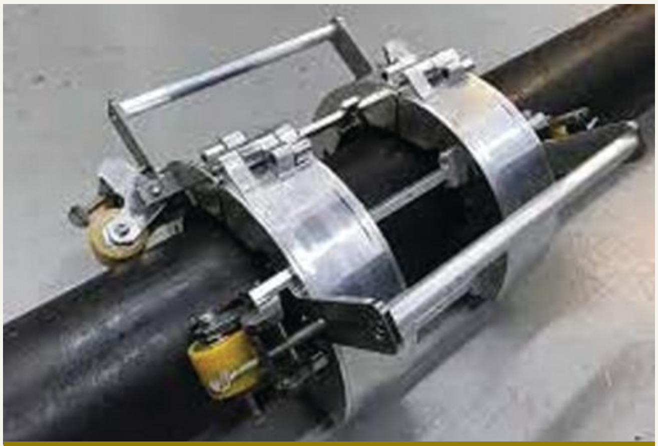
Corrosion-resistant tendon anchorage systems: anchorage for slab tendon (left) and multistrand tendon anchorage with cutaway of grout cap (right). Photos: Structural Technologies.

The presence of spalling and delamination of concrete may indicate active corrosion of the mild reinforcing steel and possible corrosion of the post-tensioning system. Concrete spalling and delamination can provide a pathway for moisture, oxygen, and contaminants from the environment to reach the prestressing steel. The quantity, frequency, and location of spalls and delaminations should be carefully mapped and evaluated.

Special attention should be given to construction and expansion joints as well as closure pours. If the expansion joints are open or the joint seals fail, water can infiltrate the joint and deteriorate the adjacent prestressing steel and anchorages, particularly where the end anchorages are not adequately protected.

- **Acoustic inspection:** Chain-drag and hammer-sounding techniques are economical and relatively accurate methods of determining the general locations and extent of concrete delamination. These methods rely on the differences in sound generated by competent concrete compared with damaged concrete. The process includes striking the concrete with a hammer or dragging a chain across the concrete surface. The change in sound can locate possible concrete voids or delamination.
- **Pacometer testing:** Pacometers can locate—and also determine the concrete cover over—mild and prestressing reinforcement with reasonable accuracy.
- **Impact-echo evaluation:** This nondestructive technique uses stress waves generated by mechanical impact to detect cracks, voids, honeycombing, and debonding in concrete structures, as well as to locate delamination caused by steel corrosion.
- **Compressive strength testing:** Cores taken in the field can be tested in the laboratory to determine the compressive strength of the concrete. Compressive strength testing (ASTM C42[4]) is conducted to assess whether the concrete strength meets the original design requirements and provide information that can be used in a structural analysis.
- **Corrosion testing:** Corrosion potential (ASTM C876[5]) and corrosion-rate testing can be used to identify active areas of possible reinforcement corrosion and the corrosion rate.
- **Chloride testing:** Chloride-ion content evaluation (ASTM C1152M,[6] ASTM C1218,[7] and AASHTO T260[8]) is performed on powder samples of concrete and/or grout from the structure. It is critical to identify the existence of high chloride concentrations because the rate of deterioration of concrete structures is affected by the presence of chloride ions in concentrations above the corrosion threshold level.
- **Carbonation testing:** Carbonation of concrete is caused by the reaction of calcium hydroxide in cement paste with atmospheric carbon dioxide to form calcium carbonate, which reduces the pH of concrete. This condition makes the concrete more conducive to corrosion of the mild steel reinforcement and exposed post-tensioning hardware.
- **Petrographic examination:** Petrographic analysis (ASTM C856[9]) is a microscopic examination of concrete that evaluates the composition of concrete or post-tensioning grout and its strength, condition, and durability. Concrete specimens are prepared for examination by a trained petrographer. The examination assesses the internal structure of the concrete, deleterious compounds that may be formed, the integrity of the cement paste, air content, and the water-cement ratio of the concrete.
- **Electromagnetic investigation:** Magnetic flux leakage (MFL) subjects the steel tendon to a strong magnetic field to determine the extent of corrosion and/or wire breaks in a post-tensioning tendon. At locations where there is section loss or wire breaks, the magnetic field in the tendon is disturbed and is recorded by sensors. This technique can be used on external tendons and stay cables but is generally not applicable for internal tendons.

Inspection of a void in a grouted post-tensioning duct using a borescope. Photo: Structural Technologies.



Magnetic flux leakage technology being used on an external tendon to detect section loss and wire breaks in post-tensioning strands. Photo: Infrastructure Preservation Corporation.

- **Ground-penetrating radar:** Ground-penetrating radar is used to locate tendons and steel reinforcing bars in slabs and web walls. An electromagnetic pulse is reflected by interfacial surfaces (changes in density or layers of different types of materials), and the reflected wave is received and analyzed. This technology can also be used to identify voids in grouted tendons and poorly consolidated regions of the concrete member.
- **Borescope inspection:** A borescope provides a visual image of difficult-to-see areas, which may include post-tensioning anchorage components and inside post-tensioning ducts where voids are discovered or expected.
- **Prestressing steel strength testing:** To assess the strength of post-tensioning strands, tensile testing of removed samples is conducted. Seven-wire strand is tested in accordance with ASTM A370.[10]

Existing Bridge Analysis Methodology

Review Original Design and Specifications

Review of the original design and specifications is guided by the goals of the rehabilitation. The design drawings, specifications, and load rating capacity should be reviewed to determine, for example, what design loads were used, material strengths, creep and shrinkage assumptions, design specifications, and assumed segment ages at erection. Design details that would impact durability such as concrete cover and drainage details should be evaluated for their potential to limit the bridge's durability or capacity relative to the rehabilitation goals. The post-tensioning system should also be reviewed to determine if known issues such as grouting problems are present. The load rating can also provide insight as to whether additional capacity was built into the original design.

Model the Existing Structure

The existing bridge should be modeled with the as-built construction sequence and actual casting and erection schedule. Time-dependent creep and shrinkage parameters should be updated to the more refined model of the *fib Model Code for Concrete Structures 2010*.[11] Use of the actual concrete strengths is an option; however, the actual concrete cylinder breaks should be evaluated, and actual 28-day concrete strength should be back-calculated statistically for use in the analysis. Inspection reports should be thoroughly reviewed to determine the level of cracking and whether linear-elastic behavior is a valid assumption for all locations within the structure, or whether section loss or nonlinear behavior should be considered. Any distress such as cracking should be reviewed to determine whether cracks are systemic or random. If cracking is systemic, the behavior that correlates to the distress observed in the bridge should be confirmed through the elastic model and the model should be updated accordingly. This procedure allows the current state of stress in the structure to be determined and leads to a better evaluation of the proper repair technique to achieve the rehabilitation goals of the project.

Repair Design Considerations

Repair strategies are developed based on rehabilitation objectives, which can involve considerations such as restoring strength and durability, cost, and aesthetics. There are many types of repair methods available, such as epoxy injection, retrofit post-tensioning, and external carbon-fiber fabric wrapping. Epoxy injection can restore structural sections; however, it should be noted that the elastic modulus of epoxies is approximately 15% that of concrete, as this fact may need to be considered for large cracks and repair areas. Retrofit post-tensioning can consist of external tendons that can be straight or deviated to add both moment and shear capacities while also adding beneficial precompression. The tendon layouts should also take into account that local anchorage and deviator stresses can be induced into the existing structure. Surface-mounted post-tensioning can also be used to address local stress concentration issues. Application of external carbon-fiber fabric wrap can add significant capacity to a structure. These are just a few of the repair options that can be used to develop a complete repair and rehabilitation strategy.

Conclusion

There is a wealth of valuable experience and advanced technologies to leverage for repairing and extending the service lives of segmental concrete bridges. A forthcoming article will describe common defects found in segmental construction and present case studies that demonstrate in greater detail repair solutions for strengthening and protecting these important structures.

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Rehabilitating the Arlington Memorial Bridge: Restoring a Monument

by Shane R. Beabes and Steve A. Matty, AECOM

More than just a bridge crossing the Potomac River, the Arlington Memorial Bridge holds a unique place in the fabric of Washington, D.C. A historic structure and integral part of the regional transportation network, the 2216-ft-long, 94-ft-wide bridge is a monument to reunification after the Civil War and carries more than 65,000 vehicles daily, linking northern Virginia to Washington, D.C. After years of service, major rehabilitation work was required to maintain this notable bridge, which sits among some of the most recognizable national landmarks.

Revitalizing the 87-year-old crossing posed a challenge as unique as the bridge itself. The National Park Service (NPS) and the Federal Highway Administration (FHWA), which jointly administer and maintain the bridge, established a 1000-day schedule to complete the project—the first major reconstruction for the bridge and one of the largest projects in NPS history. The goal was to restore the structural integrity of the bridge and preserve its historical character and context while minimizing disruption to the traveling public.

Carefully considered decisions, including materials selection, construction techniques, and innovative technologies, enabled the project team to meet the requirements of FHWA and NPS and reopen all lanes of the bridge on December 4, 2020.

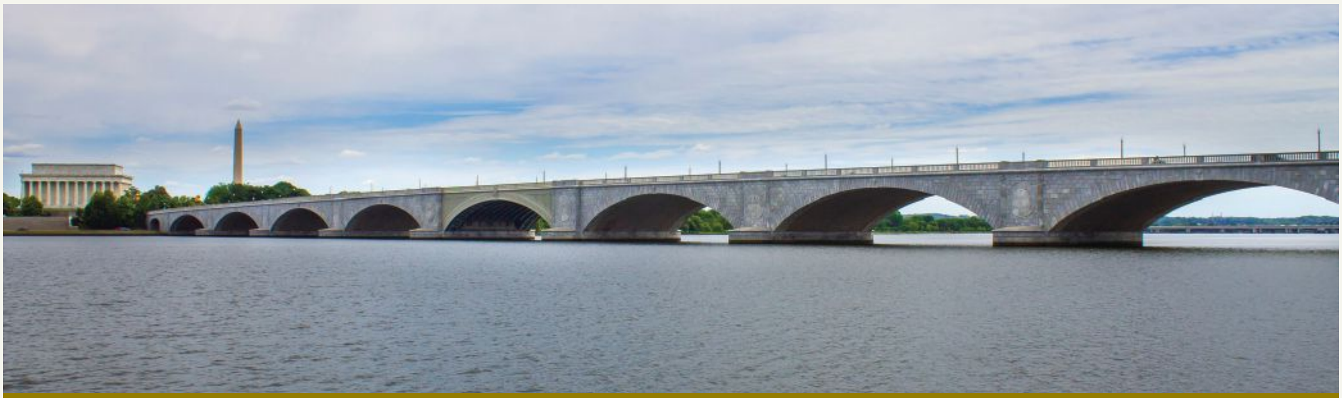
Bridge Overview

The existing bridge is a complex structure, consisting of 10 reinforced concrete arch approach spans and a center double-leaf steel bascule span over the navigable channel. The approach spans are composed of a concrete deck intermittently supported on transverse concrete cross walls on top of the concrete arch rib. The deck and cross walls also tie into the reinforced concrete spandrel walls adorned with granite fascia that close in the span. The bridge also includes four abutments and six concrete piers, each of which contains concrete frames and transverse cross beams designed to support the roadway deck. The frames are supported on the abutments and pier footings that ultimately transfer the loads down to bedrock. During the reconstruction process, most elements of the bridge required some form of intervention: rehabilitation, reconstruction, or preservation.

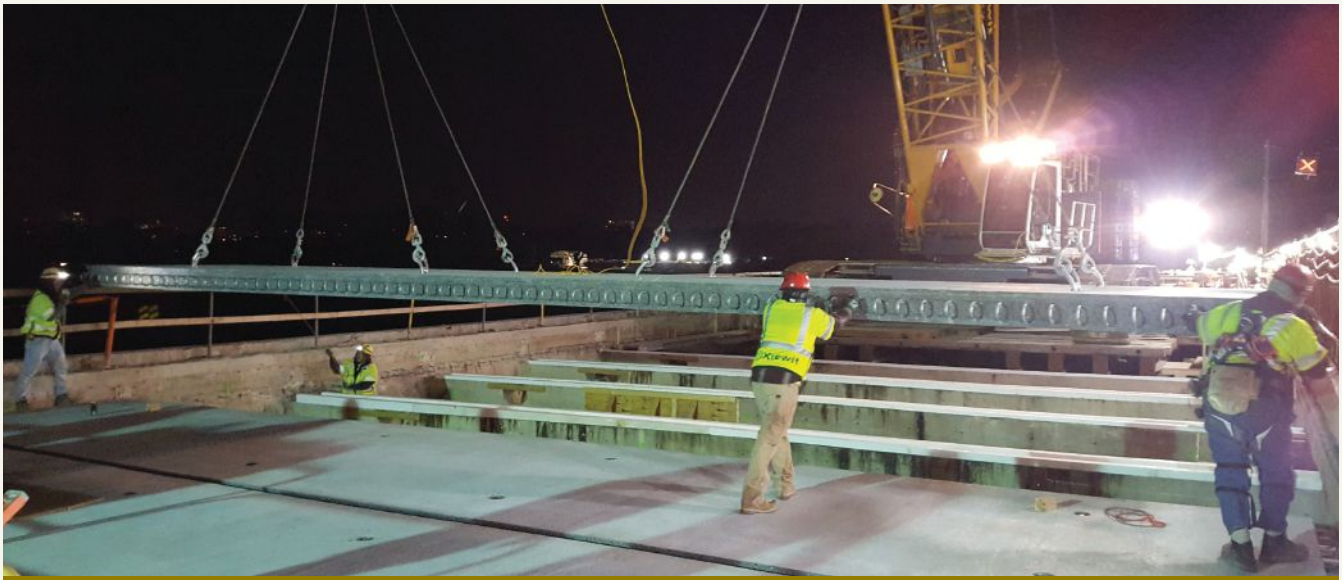
Materials

Precast and Field-Cast Concrete

Whereas the original bridge structure used cast-in-place concrete, which was standard at the time, the team used precast concrete panels to replace the entire deck during the rehabilitation process. Using precast concrete for the new deck expedited the construction process by enabling the existing deck to be removed while the precaster was completing the



The Arlington Memorial Bridge is a monument to reunification after the Civil War and carries more than 65,000 vehicles daily, linking northern Virginia to Washington, D.C. Photo: AECOM.



Precast concrete deck panels were installed at night, when traffic volumes were low. Panels span between the cross walls that are visible in the center of the photo. The bridge was generally closed for only about 15 minutes at a time when a panel was picked and rotated into place. Photo: Pennstress.

new deck panels off site—a critical factor when considered in the context of the short rehabilitation time frame.

The precast concrete deck panels are 10 in. thick and constructed of 6000-psi high-performance concrete (HPC) with stainless steel reinforcement, providing reduced permeability and greater durability than the original deck, which used 3000-psi concrete and uncoated reinforcing steel. The precast concrete deck panels were set piece by piece to span between the cross walls visible in the nighttime photo above. The deck panels in the approach spans were designed to span longitudinally between the arch cross walls, whereas the deck panels in the new fixed center span were designed to span transversely between the longitudinal steel girders. A 2-in. latex-modified concrete overlay was placed on top of the precast concrete deck panels to provide additional protection for the precast concrete deck and a smooth riding surface.

HPC with 28-day compressive strengths ranging from 4500 to 6000 psi was used for the two 14-ft-wide shared-use sidewalks, approach slabs, cross walls, precast concrete beams, pier caps, columns, and precast concrete deck panels.

Ultra-High-Performance Concrete

The selection of ultra-high-performance concrete (UHPC) and HPC was a critical component of the bridge reconstruction because these materials provided the strength and durability required to meet the project's needs.

The stainless steel hairpin reinforcing bars extending from the precast concrete deck panels overlapped, creating a highly reinforced joint that was filled with ultra-high-performance concrete (UHPC). The exposed aggregate finish on the edges of the panels promoted bond with the UHPC. Photo: AECOM.

Ultra-high-performance concrete is a high-strength, dense concrete that incorporates random steel fibers and reduces permeability to water, chlorides, and other deleterious materials. It provided a minimum 28-day compressive strength of 21,000 psi for this project. Photo: AECOM.

As panels were set into place, the hairpin reinforcing bars extending from the panels overlapped, creating a highly reinforced joint between deck panels and with the cross walls or girders. This joint was then filled with UHPC, a high-strength, dense concrete that incorporates random steel fibers and reduces permeability to water, chlorides, and other deleterious materials. The UHPC on this project had a minimum 28-day compressive strength of 21,000 psi and a minimum 4-day compressive strength of 15,000 psi, which enabled the deck to meet the performance requirements.

Accelerated Bridge Construction and Traffic Management

To sequence the overall construction to minimize construction impacts to the traveling public, the team used accelerated bridge construction methods with six construction stages for the project. Two major construction stages temporarily reduced the six 10-ft-wide travel lanes to three 9-ft-wide lanes with a reversible center lane; this arrangement allowed the team to close half of the bridge at one time while the other half remained open. The process started on the bridge's south side with traffic maintained on the north side. Traffic was then switched to the south side for substantial completion of the remaining work. During construction, one of the two 14-ft-wide shared-use paths remained in service at all times.

Delivering the precast concrete deck panels at night, when traffic volumes were low, reduced congestion and delays. Even at night, the bridge was generally closed for only brief intervals (about 15 minutes) when a panel was picked and rotated into place. The precast concrete panels were designed to extend from the spandrel wall to the middle of the bridge cross section, creating a longitudinal closure joint the full length of the bridge. This joint was also filled with UHPC after the panels were set.

Innovation: Cathodic Protection System

Whereas the deck, concrete frames, and selected cross walls needed to be replaced, testing revealed that the original concrete arch ribs and most of the transverse cross walls were structurally sound. Experts on the design team developed a cathodic protection system to preserve and extend the service life of the remaining preexisting concrete elements. This system uses sacrificial galvanic anodes embedded into the concrete to protect the surrounding steel reinforcement from further corrosion.

Conclusion

Rehabilitating a bridge is rarely simple; rehabilitating a historic landmark is even more complex. The revitalization of the Arlington Memorial Bridge, with all of its complexities and historical significance, is a testament to the use of innovative techniques, thoughtful material selection, and carefully considered coordination among the NPS, the FHWA, and the Kiewit-AECOM team from beginning to end. The completion of the bridge rehabilitation not only ensures mobility across the region but also fortifies a monument to sacrifice and valor that will remain a symbol of our collective history for generations to come.

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Two major construction stages temporarily reduced the six 10-ft-wide travel lanes to three 9-ft-wide lanes with a reversible center lane, allowing for closure of half of the bridge while the other half remained open. One of the two 14-ft-wide shared-use paths remained in service at all times. Photo: AECOM.

Erection of 155-ft-long, 85-in.-deep lightweight concrete bulb-tee beam.
Photo: *Whitman, Requardt & Associates*

Lightweight Concrete Bridges in Virginia

The Atkinson Boulevard Bridge Project in Newport News, Virginia, was featured in the Fall 2021 issue of *ASPIRE*®. This project is a good example of the progress made in Virginia regarding the use of lightweight concrete for girders and decks in bridges. Lightweight concrete had been used occasionally for decks constructed in the state over the years. But recently, as the result of collaboration between the Virginia Department of Transportation (VDOT) and researchers at the Virginia Transportation Research Council (VTRC, VDOT's research arm), several successful demonstration projects using lightweight concrete have been completed, design guidance has been developed, and its use has become more common.

For the project in Newport News, the selection of lightweight concrete early in the project allowed the designers to eliminate a girder line. Using lightweight concrete with a design density of 120 pcf for both deck and girders also reduced foundation loads, decreasing the number and length of piles required to support the structure. These factors resulted in significant savings. The designers also found that the number of prestressing strands in each girder was reduced which helped offset the added cost for the lightweight concrete and also reduced camber growth. Refined analysis methods were used to evaluate the long-term behavior of the nearly 1750-ft-long bridge, which only had joints at the abutments. Working with the contractor and fabricator, the designers were able to predict cambers well enough to avoid camber-related problems during construction.

Lightweight concrete was also seen as providing a durable solution. The VDOT *Road and Bridge Specifications* recognize the improved cracking resistance of lightweight concrete by including it as an option for their low cracking Class A4 modified concrete, which is generally used for decks.

Another bridge with lightweight concrete girders and deck is currently being constructed not far from the Aktinson Boulevard site. Others have been constructed, including a small bridge that was featured in the Summer 2017 issue of *ASPIRE*.

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Latex-Modified Concrete Use in Low Temperatures and Extended Wet-Cure Conditions

by Chuck Fifelski, Trinseo

Many roads and bridges across the United States were constructed in the 1960s and 1970s. Because traffic and truck loads have increased since then, more than one-third of U.S. bridges now need repairs or replacement.[1] Bridge maintenance is critical because a sound infrastructure improves our daily quality of life and offers a global competitive advantage.

Latex-modified concrete (LMC) plays an integral role in the story of our nation's infrastructure maintenance and repair. The use of latex as a performance-enhancing additive in modified concrete systems for bridge deck overlays is a proven technology. With a combination of excellent compressive, flexural, and bond strengths, an LMC overlay is one of the best choices for many bridge and roadway repair projects.

An Introduction to LMC

LMC is a modified concrete designed to meet latex specifications and concrete performance criteria suggested in the Federal Highway Administration (FHWA) report *Styrene-Butadiene Latex Modifiers for Bridge Deck Overlay Concrete* (FHWA RD-78-35).[2] Latex materials can be tested to determine whether the properties meet the FHWA report's criteria.[3] LMC has been recognized for its longevity, superior performance, and overall economic advantage when used for bridge deck overlay repair.[4]

LMC was designed for thin, bonded overlays and can provide a service life of more than 30 years when placed properly. Studies performed by the Virginia Transportation Research Council[5] and the Strategic Highway Research Program[6] conservatively estimate that LMC can last between 22 and 26 years. Because of this longevity, LMC is often used on bridge decks, highway overlays, parking decks, and other roadways where surface rehabilitation is required.

LMC's appeal comes from three main properties:

- Bond strength typically exceeds the strength of the base concrete.
- Low modulus of elasticity makes the overlay more flexible and less brittle.
- Low permeability reduces moisture and chloride-ion penetration, which helps protect reinforcing steel from corrosion.

Thanks to these properties, LMC overlays require less maintenance and have lower overall costs over the life of the bridge compared with other repair alternatives.

One drawback of LMC, as with many concrete systems used for bridge deck overlays, is that the installation season is limited in the spring and fall when temperatures are cooler. However, a low-temperature cure study conducted by Trinseo showed that LMC cured under longer wet-cure conditions and lower temperatures can still obtain the required compressive strength, thus demonstrating its efficacy under these conditions.

Curing Study Results

State departments of transportation (DOTs) have varying requirements for LMC curing conditions; however, typical specifications require two days of wet curing followed by two to three days of air drying. The air drying enables the polymer in the concrete matrix to coalesce, thereby developing the water and chloride-ion penetration resistance for which LMC is known. Freshly placed LMC must also be protected from cold temperatures. Curing blankets are recommended to help maintain heat when the air temperature drops below the specified minimum, typically 45°F to 50°F depending on the DOT. In isolated cases, there is concern that curing blankets, although useful for temperature maintenance, can hinder air drying and the development of chloride-ion penetration resistance.

A study of the impact of using curing blankets was conducted to evaluate the effects of low curing temperatures on the development of compressive strength and chloride-ion penetration resistance. The study simulated extended wet-cure conditions. It followed FHWA criteria[2] for LMC mixture proportions, which help ensure that a mixture can be placed and handled in a similar fashion as conventional concrete. **Table 1** shows the cure conditions to which the test cylinders were subjected. The cylinders were then tested for compressive strength and chloride-ion penetration at various time intervals. Testing was performed in accordance with methods specified by ASTM International[7] and the American Association of State Highway and Transportation Officials.[8]

The study concluded that the extended wet cure using curing blankets is not detrimental to compressive strength development or chloride-ion penetration resistance (**Fig. 1** and **Table 2**).

The results for the compressive strength tests were excellent under all cure conditions. The extended wet cure was used to simulate the use of blankets, and results showed excellent strength development; therefore, the use of blankets is not expected to negatively affect compressive strength development. The compressive strength of LMC specimens cured under longer wet-cure conditions and/or lower temperatures continued to increase at 28 days, and

Table 1. Curing profile description and details for latex-modified concrete samples

	Control*	Control* and freezing	5-day wet cure	5-day wet cure and freezing	Constant 50°F	Fall profile	Spring profile
Cure condition	Days at each cure condition						
Wet cure at 50°F	2	2	5	5	2	2	2
Air dry/cure at 50°F	3	3	n/a	n/a	26	n/a	10
Air dry/cure at 20°F (freezing)	n/a	2	n/a	2	n/a	n/a	n/a
Air dry/cure at 72°F	23	21	23	21	n/a	10	8 at 60°F
Air dry/cure at 60°F	n/a	n/a	n/a	n/a	n/a	8	8 at 72°F
Air dry/cure at 50°F	n/a	n/a	n/a	n/a	n/a	8	n/a
Total days	28	28	28	28	28	28	28
Additional curing							
Air dry/cure, days	90 (total) at 72°F	90 (total) at 72°F	90 (total) at 72°F	90 (total) at 72°F	90 (total) at 50°F	90 (total) at 50°F	90 (total) at 72°F
Air dry/cure	6 months (total) at 72°F	6 months (total) at 72°F	6 months (total) at 72°F	6 months (total) at 72°F	6 months (total) at 50°F	6 months (total) at 50°F	6 months (total) at 72°F

n/a = not applicable.
*Control represents standard curing conditions.
Table: Trinseo.

at 90 days where data were available. At 90 days, the compressive strengths were essentially equivalent for all cure conditions for which data were available. For the two conditions where 90-day test data were unavailable, the 28-day test values were roughly equal to or well above the other 28-day test results, so the 90-day values could be expected to be at least equal to test results for the other conditions.

The study also showed that chloride-ion penetration resistance improved over time (that is, test results were lower) under all curing conditions, demonstrating that extended wet-curing periods and/or lower temperatures are not detrimental. Table 2 shows that resistance to chloride-ion penetration after six months was better for all specimens with longer wet-cure conditions and/or lower temperatures than for specimens with standard curing. The specimens with 5 days of wet curing exhibited the best chloride-ion penetration resistance at each test interval, whereas the specimens with extended low temperatures during curing developed chloride-ion resistance more slowly than other systems but still achieved values lower than specimens subjected to the control curing conditions.

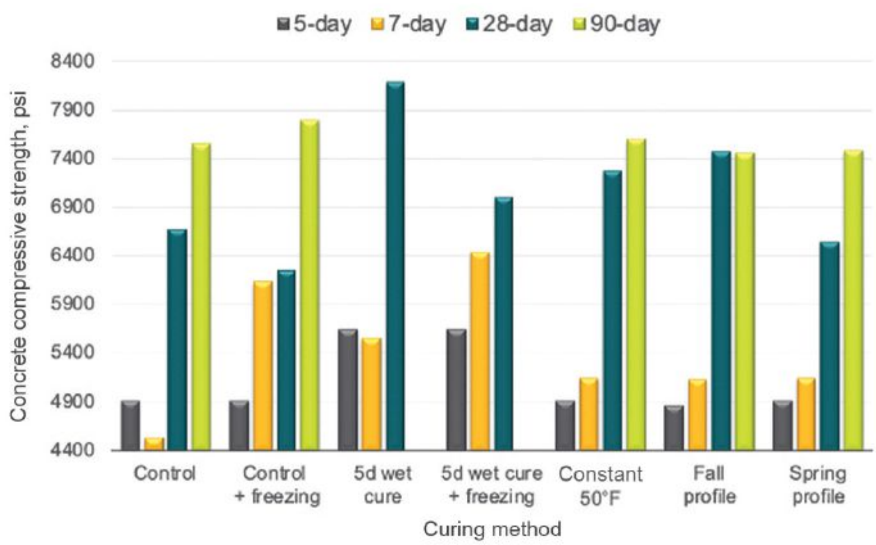

Figure 1. Compressive strength of latex-modified concrete samples under different curing conditions from the average of three cylinders tested according to ASTM C39.[7] Figure: Trinseo.

Concrete Repair Implications

The results of the study are good news for concrete professionals looking to repair concrete bridge decks by placing LMC overlays quickly, effectively, and cost efficiently, while navigating state regulations for minimum temperatures and cure times. The results confirm the efficacy of curing blankets to maintain temperature without affecting LMC performance, thus contributing to an extended installation season and allowing overlays to be reopened to traffic in an expedited fashion.

Table 2. Electrical charge passed (coulomb) as an indication of ability of latex-modified concrete to resist chloride-ion penetration (average of three tests according to AASHTO T277)[8]

Age tested (average of 2 cylinders)	Control*	Control* and freezing	5-day wet cure	5-day wet cure and freezing	Constant 50°F	Fall profile	Spring profile
	Adjusted readings, coulomb						
28 days	2507	2639	1921	2437	3677	2803	2700
90 days	1229	1124	1002	1247	1401	1433	1137
6 months	821	831	692	793	801	795	788

Definitions for chloride-ion penetrability ratings	High	Moderate	Low	Very low	Negligible
Charge passed, coulomb	>4000	2000–4000	1000–2000	100–1000	<100

*Control represents standard curing conditions.
Table: Trinseo.

A crew places a latex-modified concrete overlay with good flow and consistency. All Photos: Pat Martens, Bridge Preservation & Inspection Services.

For those considering LMC for their next bridge deck overlay repair project, look for products that meet the criteria suggested in FHWA RD-78-35.[2] Using a product that meets these criteria will ensure that your project benefits from similar performance properties exhibited in this study.

Future studies should evaluate whether LMC will cure properly under even lower ambient temperatures. A better understanding of performance under different environmental conditions will help better define seasonal placement limitations and preferred curing conditions for LMC.

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A crew places wet burlap on a latex-modified concrete overlay for optimal curing to ensure superior results.

Can Portland-Limestone Cement Be Used in Bridge Construction?

by Dr. Kyle A. Riding, University of Florida

In the near future, portland-limestone cement (PLC) is expected to become the dominant cement available and in use in North America because of its many benefits for both concrete and the environment. PLC has a long history of successful use in concrete. It has been successfully used in Europe for at least three decades.[1] It has been sold in the United States as a Type IL cement with 5% to 15% interground limestone fines under *Standard Specification for Blended Hydraulic Cements* (ASTM C595[2]/AASHTO M240[3]) for use in transportation infrastructure since 2012. Cement containing up to 15% limestone fines has been allowed in Canada since 2008.[4] The Colorado Department of Transportation has been allowing PLC since 2007, and most other state departments of transportation now allow PLC use in at least some applications. However, some contractors, material suppliers, and specifying agencies in the United States are hesitant to use PLC because they have questions about its performance. In this article, I will address some of the most common questions and myths about PLC, discuss some of its advantages, and hopefully convince you to use it in the near future.

What Are the Driving Forces Behind PLC Adoption?

PLC has a lower environmental footprint than ordinary portland cement (OPC) meeting the *Standard Specification for Portland Cement* (ASTM C150).[5] Because limestone fines do not need to be heated or chemically changed during manufacture, Type IL cements can have up to 10% lower carbon dioxide (CO_2) emissions than equivalent OPC.[6] Government regulations in some areas have imposed limits or pricing on greenhouse gas emissions that apply to cement plants. Many cement manufacturers have adopted policies to reduce greenhouse gas emissions, even in areas where limits are not required by law. If a plant has sufficient grinding capacity, use of limestone fines in the cement can also increase cement plant production capacity at low additional cost. Some U.S. plants have converted or will soon convert to 100% PLC production.[7,8] In the near future, OPC may not be available in your area, leaving PLC as the only option. Thankfully, PLC can make concrete that is as good as or, in some cases, even better than concrete made with OPC.

Does Use of Limestone in the Cement Hurt the Strength?

There is a misconception that limestone fines are not reactive, do not contribute to strength, and only dilute the binding capability of portland cement. Most cement producers grind Type IL cements to have about 100 m²/kg higher Blaine fineness than a Type I cement made with the same clinker to give similar setting time, strength gain rates, and heat of hydration.[4] When used at up to 15% by mass of cement, the limestone fines are not inert and can actually react chemically with the alumina-bearing compounds in the cement.[9] The small limestone particles also enhance the reactions from the other cementitious materials by creating better particle size distribution and better filling in empty space in a phenomenon called the filler effect. Additionally, they provide nucleation locations to enhance the

Figure 1. Ultra-high-performance concrete made with Type IL cement during flow testing. Figure: Megan Voss.

clinker reaction and are beneficial to the concrete properties overall.

Transitioning from an OPC to a PLC does not typically require any more testing or mixture adjustment than is required when switching cement sources for the same type of cement. Type IL cements can be easily proportioned to meet the high-early strengths needed at precast concrete plants. For example, Type IL cements from multiple suppliers were able to meet 4500-psi strength requirements at 18 hours at room temperature, and greater than 6000-psi strength at 18 hours when cured at simulated precast concrete temperatures.[10] High-early-strength PLC can be specified as a Type IL (HE) cement to give similar strength gain rates as Type III cement; this allows precast concrete producers to switch to a PLC with only the same testing required when switching Type III cement sources.

In our laboratory at the University of Florida, we have been using a Type IL cement to consistently produce an ultra-high-performance concrete (UHPC) with compressive strength in excess of 10 ksi at 2 days and 18 ksi at 28 days when cured in the fog room, direct tensile strength at 28 days above 1200 psi with strain-hardening properties, and with great flowability (**Fig. 1**), demonstrating the possibilities of PLC. The smaller particle size of the limestone fines in the cement may actually help with particle packing and achieving good flows when used in UHPC. We are also finding that UHPC with Type IL cement has excellent durability against chloride intrusion, resistance to freezing and thawing, and low creep.

PLC Used with Supplementary Cementitious Materials

PLC used with supplementary cementitious materials (SCMs) that contain high alumina content, such as fly ash per the *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete* (ASTM C618),[11] slag cement per the *Standard Specification for Slag Cement for Use in Concrete and Mortars* (ASTM C989),[12] or metakaolin also per ASTM C618, reacts to provide an increase in strength and durability. The CO_2 in the limestone and alumina in the SCMs react to form carboaluminates that reduce porosity, boost strength, and improve durability. Ternary blends with limestone fines and SCMs are being introduced around the world to take advantage of this synergy, with equivalent performance to OPC with as little as 50% clinker.[13–17]

How Durable Is PLC?

Concrete made with ASTM C595 Type IL cement has similar or better durability compared with concrete that uses an ASTM C150 cement made with the same clinker. The following summarizes the durability of PLC concretes against different forms of deterioration compared with OPC concretes:

- Chloride penetration resistance, chloride binding, and time to corrosion initiation are similar for limestone fines addition up to at least 15%.
- Sulfate-attack durability is mostly a function of the tricalcium aluminate content, water–cementitious materials ratio (*w/cm*), and type and amount of SCMs used, not of the limestone fines content.[18] There was a concern when PLC was first considered for adoption in North America that use of limestone fines in cement in environments with low-temperature sulfate exposure would lead to a particularly damaging form of sulfate attack called thaumasite formation. However, studies have found no significant difference in durability in sulfate exposure based on limestone additions in the ranges used in commercially available Type IL cements.[19,20] Sulfate durability of PLC can be significantly enhanced with use of SCMs such as metakaolin (**Fig. 2**).
- PLC systems have equivalent or better alkali-silica reaction performance compared with OPC systems.[18]
- PLC and OPC systems also have equivalent resistance to freezing and thawing, with both depending on the percentage of air entrainment. No significant difference in salt-scaling resistance is expected.[21]
- Shrinkage is similar (within 10%) in PLC and OPC sytems, as long as the PLC is not ground more than 30% finer than the OPC and typical *w/cm* limits applied to bridge members are followed. Overall, greater precautions are not needed to prevent shrinkage-related cracking in commercially available PLC systems.[10,18,22]

Conclusion

PLC is ground slightly finer than OPC to give equivalent strength and durability to the concrete. In most jurisdictions, the testing effort required to switch from the use of OPC to PLC in concrete mixtures should be the same as the effort needed to switch between OPCs made at different cement plants. Type IL (HE) cement can achieve concrete strengths at early

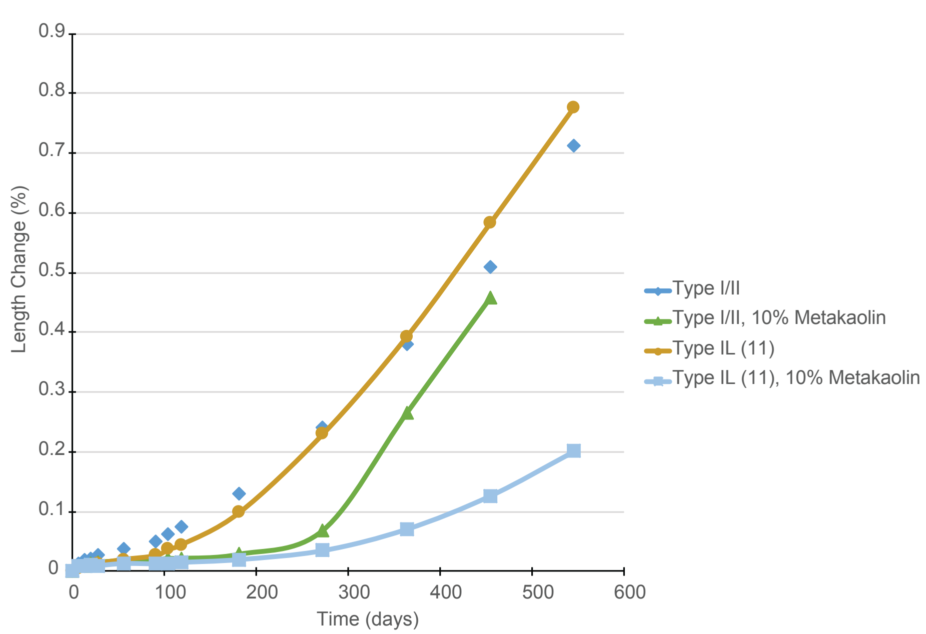

Figure 2. Sulfate attack durability of Type I/II and Type IL cement with and without 10% metakaolin. Note: Type IL (11) indicates Type IL cement with 11% limestone fines.
Figure: Alyami, M. H. M. 2019. "Sulfate Attack on Concrete: Potential for Accelerated Test Methods for Physical Salt Attack of Concrete." PhD diss., University of Florida.

ages equivalent to that achieved with a Type III cement for precast concrete applications. Type IL cement can be used to make concrete with compressive strengths greater than 18 ksi with excellent durability properties, allowing it to be used in nonproprietary UHPC. In the near future, concrete producers may not have other options as cement plants begin to produce only PLC.

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Welded Wire Reinforcement: A Primer for the Bridge Designer, Part 1

by Paul Aubee, Artisan Structural PLLC

Welded wire reinforcement (WWR) is mild steel reinforcement for structural concrete with a long-standing acceptance in reference design standards such as the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] and the American Railway Engineering and Maintenance-of-Way Association's (AREMA's) *Manual for Railway Engineering.*[2] The material is manufactured in accordance with the requirements of ASTM A1064, *Standard Specification for Carbon-Steel Wire and Welded Wire Reinforcement, Plain and Deformed, for Concrete.*[3]

WWR manufacture starts with the cold-working of hot-rolled steel rods through dies or rollers to produce structural wires of specified diameters. These wires are then run through programmable, highly automated machines on which the wires are arranged and then securely connected at intersections by an electric resistance welding process. This welding method combines pressure and the passage of electrical current through the interface of the orthogonally intersecting wires to create fused joints.

Attributes

The following attributes of WWR mats are noteworthy.

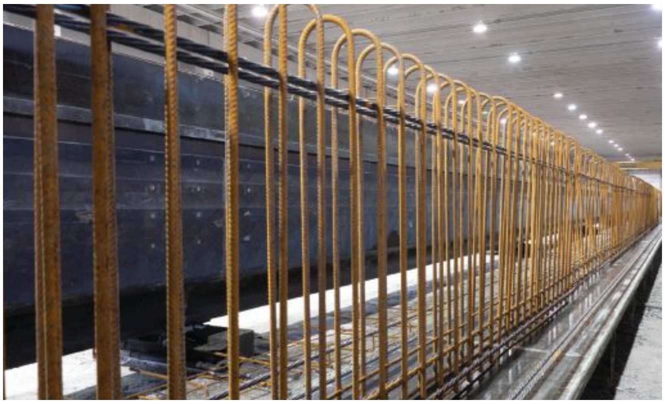
Wire surface: Wires of a WWR mat can be either deformed or plain. Deformed wires are characterized by surface protrusions or indentations that, similar to deformed reinforcing bars, develop bond at the interface with hardened concrete primarily through a bearing mechanism. Plain wires are characterized by a smooth wire surface.

Dimensional flexibility: Wire diameters range from approximately 0.100 to 0.628 in., the latter being roughly equivalent to a no. 5 reinforcing bar. Wire spacing is also variable, with increments ranging from as small as 2 in. up to a maximum spacing of approximately 8 ft, an interval driven more by transport and handling limitations than by the manufacturing equipment or ASTM A1064 requirements. With this in mind, it is common for WWR mats to have variable wire sizes and spacings in both the longitudinal and transverse directions. Furthermore, it is possible for both deformed and plain wires to be part of a single WWR mat.

Size and fabrication: WWR mats can be manufactured in widths up to roughly 12 ft and lengths exceeding 40 ft. It is possible to produce mats with variable wire lengths in a common direction, which is another example of the versatility of modern WWR manufacturing equipment. Flat mats can then be taken from the welding equipment directly to a bending station, where the mats are fabricated into shapes to suit the profile of the structural element into which they will be placed at the precast concrete plant or on the jobsite.

Structural design: Calculation of flexural, torsional, axial, and shear sectional strengths using design procedures established in the AASHTO LRFD specifications and the AREMA *Manual for Railway Engineering* is straightforward for WWR: The design equations are identical to those for individual deformed bars or wires. Only the development length, lap splice length, and limitations for seismic applications are different.

Strength: WWR with a yield strength up to 80 ksi is commonly produced at no premium, with 70 ksi being standard



Welded wire reinforcement installed as the stem reinforcement for an inverted-tee section. Note the 180-degree bends at the top and the longitudinal anchor wires at the bottom of the mats. All Photos: Wire Reinforcement Institute.

Following the installation of the stem welded wire reinforcement (WWR) in an inverted-tee section, the bottom-flange reinforcement is installed in the form of bent WWR mats.

The bundle of mats shown here—characterized by varying lengths of individual reinforcement pieces all automatically assembled and welded—is an example of the versatility of modern welded wire reinforcement manufacture.

for welded deformed wire reinforcement and 65 ksi being standard for welded plain wire reinforcement. The AASHTO LRFD specifications currently allow reinforcement with a yield strength of 75 ksi, increased to 100 ksi for certain applications, whereas the AREMA manual requires designs to be based on a 60-ksi maximum yield strength.

Tension development and lap splice lengths: For welded deformed wire reinforcement, the designer can calculate development length and lap splice length based either on a combination of contributions by welded intersection anchorage and deformed wire surface or on the deformed wire surface alone. In the case of the former calculation, the combined contribution of welds and deformed surface can result in reduced development and lap splice lengths. The latter calculation essentially defaults to equations used for loose individual pieces of deformed bar or wire. For welded plain wire reinforcement, because the smooth wire surfaces are incapable of bond with the surrounding hardened concrete, development length and lap splice length calculations are based entirely on anchorage provided by the welded intersections.

Prebent welded wire reinforcement mats are used here as girder bottom-flange confinement steel.

Use in Bridge Elements

There is perhaps no better example of the utility and economy of WWR than the bridge girder. Although the scale of these elements is typically such that flexural capacity is primarily achieved through the use of prestressing steel, practically all other mild steel reinforcement applications within a girder are well suited to a WWR solution.

Vertical stem or transverse reinforcement to suit varying magnitudes of shear demand along the member's length is easily managed in the form of modules of WWR mats fabricated with variable wire sizes and spacings to suit the design. The vertical wires of these mats can terminate in standard hooked anchorages at their ends, or they can derive anchorage from welded structural anchorage wires. Both options are commonly manufactured, with the latter's popularity born out of a desire to minimize interference between hooked terminations and other embedded features without compromising the anchorage of the shear reinforcement legs.

Girder top-flange reinforcement in both the transverse and longitudinal directions is a natural fit for flat WWR mats, with the solution composed of mat modules that are installed such that longitudinal wires can lap end-for-end along the girder's length. Likewise, girder bottom-flange confinement reinforcement is often fabricated in the form of prebent WWR modules. Bent WWR mats are also used in the prestressing anchorage zones at girder ends, where control of bursting forces is critical.

WWR has been successfully deployed in I-beams, bulb-tee girders, segmental box girders, and slab beams. Additionally, WWR continues to be a popular mild steel reinforcement solution for cast-in-place bridge decks, slip-formed barrier rails, precast concrete arch bridges, and box culverts.

The Benefits

For the design professional, there is ease in having design interchangeability between WWR and individual reinforcing bars in the provisions of the AASHTO LRFD specifications and AREMA manual. This opens the door to the most tangible benefits of WWR: the contractor's ability to greatly reduce installation time and streamline the allocation of labor for reinforcement placing activities, all while installing a structural reinforcement with unparalleled control of fabrication and placement tolerances. These on-site advantages over loose reinforcement have never been more valuable given today's climate of increasing labor shortages and accelerated construction timelines.

A future article will discuss best practices for implementing WWR in contract drawings and the critical role played by the manufacturer's WWR detailing staff in preparing shop drawing and placement submittals for engineer and contractor reviews.

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Welded wire reinforcement (WWR) mats in place before the concrete pour for a bridge girder. WWR is used in the girder stem and both flanges.

Changes to CRSI Standard Bar Bend Diameters for Stirrups and Ties

by Dr. Krista Brown

Many readers may still be unaware of changes made in the Concrete Reinforcing Steel Institute's (CRSI's) latest edition of the *Manual of Standard Practice*[1] regarding minimum inside bar bend diameters for no. 3, 4, and 5 steel reinforcing bars that are used for stirrups and ties. This change was recently brought to the attention of the *ASPIRE*® team by a precaster.

What Is the Change?

In 2018, CRSI published the 29th edition of its *Manual of Standard Practice*,[1] including changes to Table 7-2 (**Fig. 1**) which lists the minimum inside bar bend diameters as 2, 2½, and 3¼ in. for no. 3, 4, and 5 stirrups and ties, respectively. In general, these values equate to a minimum bend diameter of five bar diameters ($5d_b$) for all grades, instead of four bar diameters ($4d_b$) as given in earlier CRSI manuals and other current specifications and standards such as the American Concrete Institute's *Building Code Requirements for Structural Concrete* (ACI 318-19) *and Commentary* (ACI 318R-19)[2] and the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[3] **Table 1** compares the minimum inside bar bend diameters for different specifications and standards.

ASTM A615/A615M-20, *Standard Specification for Deformed and Plain Carbon Steel Bars for Concrete Reinforcement*,[4] specifies pin diameters for bend tests; it does not specify minimum inside bend diameters for reinforcing bar detailing and fabrication, which are typically given in design specifications and codes. The pin diameters are fully defined in ASTM A615, which is used to determine compliance with material property requirements of reinforcing bars. The specified pin diameters for bend tests of no. 3, 4, and 5 reinforcing bars are a function of steel reinforcement grades, with a pin diameter of $3.5d_b$ required for Grades 40 and 60 and a pin diameter of $5d_b$ required for Grades 80 and 100. For larger bars, the pin diameter for bend tests is not a function of grade. Only one pin diameter is specified in ASTM A615 for no. 3, 4, and 5 reinforcing bars; no distinction is made for stirrups and ties.

Why Was the Change Made?

According to CRSI vice president of engineering, Amy Trygestad, the CRSI committee responsible for the change discussed the topic during the CRSI Fall 2017 meeting. At that time, it seemed that ACI Committee 318 was looking to adopt a $5d_b$ minimum bend diameter for no. 3, 4, and 5 stirrups and ties when adopting Grade 80 and Grade 100 reinforcement. Furthermore, the CRSI committee discussed that ASTM A615 was changing pin diameters for bend tests to $5d_b$ for steel reinforcement grades higher than 75. After consideration, the committee decided against requiring different minimum bend diameters for different grades and agreed that the 29th edition of the *Manual of Standard Practice* should be revised to reflect the change in ASTM and the anticipated change in ACI 318-19, while maintaining uniformity and simplicity of fabrication for stirrups and ties across all grades for no. 3, 4, and 5 reinforcing bars.

Table 1. Comparison of minimum inside diameters of bends for 90-degree bend of stirrups and ties

Reinforcing bar size	CRSI[1] Table 7-2	ACI 318-19[2] Table 25.3.2	AASHTO[3] Table 5.10.2.3-1	ASTM A615/ A615M-20[4] Table 3 pin diameter
No. 3	2 in. ($5.3d_b$)	$4.0d_b$	$4.0d_b$	$3.5d_b$ for Grades 40 and 60
No. 4	2½ in. ($5.0d_b$)	$4.0d_b$	$4.0d_b$	
No. 5	3¼ in. ($5.2d_b$)	$4.0d_b$	$4.0d_b$	$5.0d_b$ for Grades 80 and 100

Note: d_b = reinforcing bar diameter. AASHTO and ACI 318-19 require $6.0d_b$ for general-use bars. This table does not apply to galvanized or epoxy-coated reinforcing bars.

Table: Dr. Krista Brown.

Table 7-2 Standard Stirrup/Tie Hooks

90° Stirrup/Tie Hooks

Stirrup & Tie Hooks: 90° Bar Size	D, (in.)	A or G, (ft-in)
#3	2"	4 1/2"
#4	2 1/2"	4 3/4"
#5	3 1/4"	6"
#6	4 1/2"	1' – 0"
#7	5 1/4"	1' – 2"
#8	6"	1' – 4"

Notes:
D = Finished bend diameter
All grades and coatings (except galvanized)

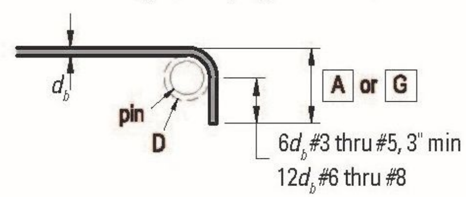

Figure 1. Minimum bar bend diameters from Table 7-2 in the Concrete Reinforcing Steel Institute's *Manual of Standard Practice*, 29th edition.[1] Minimum bend diameters for 135- and 180-degree bends are the same. Figure: Concrete Reinforcing Steel Institute.

Implications of the Change

Prestressed concrete producers have strand patterns that are somewhat "set in stone." Stress heads, bulkheads, and templates on production lines are governed by the minimum allowable distance between strands and minimum concrete cover to outside strands and stirrups. This is especially the case for bridge beams, where typically there are standard cross sections and reinforcement details that are fabricated by multiple producers. **Figure 2** compares the reinforcement details of the traditional 2½-in. ($4d_b$) bend diameter of a no. 5 tie with that of the newer 3¼-in. ($5.2d_b$) bend diameter required by CRSI. This shows that holding the corner strand in the same position would result in less cover. Typically, reduction of cover is not an option, so using fewer strands or shifting them slightly might be an alternative. Neither option is efficient. Cases with ½-in.-diameter strand and/or no. 4 bars have similar outcomes.

Figure 3 illustrates the case of a voided slab beam for which a state department of transportation (DOT) required a 2-ft 8-in. out-to-out stirrup

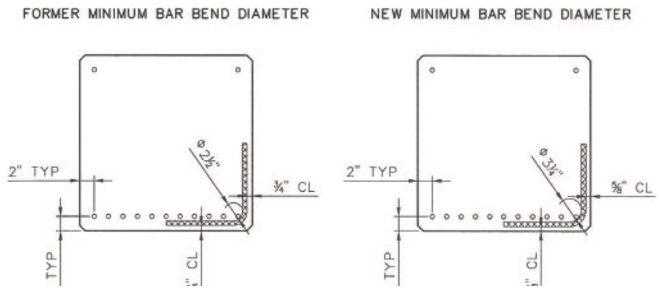

Figure 2. Comparison of no. 5 stirrup bar bends with 0.6-in.-diameter strand in the corners. The section on the left shows a typical cross section with $4d_b$ as the minimum diameter bend for a no. 5 bar with ¾ in. cover. The section on the right reflects the 3¼ in. bar bend diameter listed in Concrete Reinforcing Steel Institute's *Manual of Standard Practice*, 29th edition,[1] for the same situation. When the strand position is the same, the cover is reduced by ⅛ in. to accommodate the larger bend diameter. Figure: J.R. Parimuha.

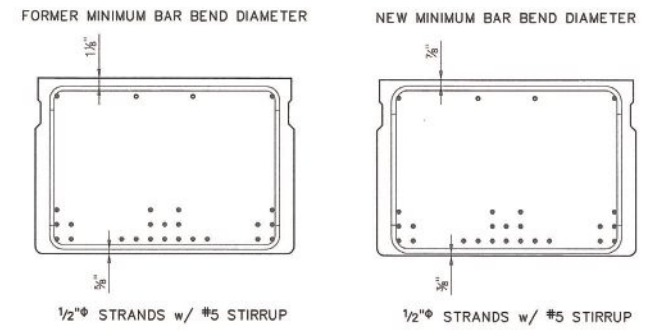

Figure 3. Effect of the larger no. 5 stirrup bar bend diameter for a voided slab cross section (voids not shown) when strand locations are the same. Due to the presence of top strands, the effect is compounded, and cover is reduced at both top and bottom. Figure: J.R. Parimuha. When the strand position is the same, the cover is reduced by ¼ in. to accommodate the larger bend diameter. Figure: J.R. Parimuha.

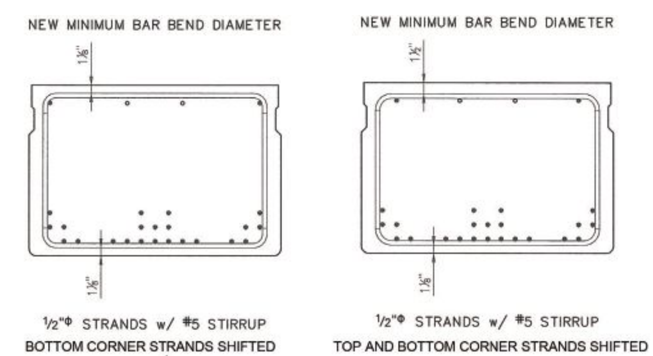

Figure 4. To meet a state department of transportation's required 2-ft 8-in. out-to-out stirrup dimension and accommodate the larger minimum bar bend diameter, a prestressed concrete producer relocated the corner strands at the top and bottom of the section inward to retain concrete cover. The alternative would have been a ¼ in. loss of cover, as shown in Fig. 3. This is not an option when all strand positions in a row are occupied. Figure: J.R. Parimuha.

dimension. In this case, the issue is compounded by the presence of top strands. With the larger bend diameter for the stirrup, the concrete cover would be decreased. **Figure 4** shows how a producer shifted the top and bottom corner strands inward to meet cover requirements while keeping the same number of strands in each row as originally designed. Because many bridge beams are optimized by placing the maximum number of strands in the bottom row, this shift is not always a viable option. If strands must be removed from the bottom row to achieve cover, placing an equivalent number of strands in higher rows reduces the moment capacity and could easily upset the delicate balance of top and bottom stresses. Shifting the entire bottom row up and/or the top row down would have similar consequences.

Exceptions to the Rules

CRSI acknowledges that there are times when specifiers and/or contractors may need special fabrication requirements, such as small bend diameters or tighter fabrication tolerances. Such requirements are commonly needed for precast concrete elements because they are often much thinner than cast-in-place concrete elements. The CRSI *Manual of Standard Practice* states in Section 7.3.2, Item 3d, that bending shapes for precast concrete units are classified as "Special Bending." CRSI does not prohibit the bending of Grade 60 stirrups and ties to the $4d_b$ bend diameter; however, the tighter bend diameter is not standard fabrication practice, is considered a special-order item, and must be clearly noted in the construction documents. To ensure that the bending operations do not damage the reinforcing bars during fabrication and that they are compliant with the AASHTO LRFD specifications, ACI 318, and the applicable ASTM specification, CRSI recommends the following for each bar size: first, the inside bend diameters specified and fabricated are equal to or larger than the applicable minimum inside bend diameter that is defined in the AASHTO LRFD specifications; second, the diameters of the bending pins used for reinforcing bar fabrication must be equal to or larger than the pin diameters described and required in the applicable ASTM specification.

—Amy Trygestad, Concrete Reinforcing Steel Institute

Who Does the Change Affect?

Use of the revised CRSI minimum finished bend diameters for no. 3, 4, and 5 stirrups and ties will affect DOTs and other agencies that reference the current edition of the CRSI *Manual of Standard Practice.* Specifications that reference the AASHTO LRFD specifications or ACI 318 are not affected, provided the ASTM A615 requirements are met. However, it should be noted that, for no. 3, 4, and 5 bars other than ties and stirrups, the AASHTO LRFD specifications and ACI 318 require a minimum bend diameter of $6.0d_b$.

What Is the Status?

The CRSI fabrication committee has formed a task group to issue a position statement for clarification on the bar bend changes, as well as how those changes relate to ACI 318-19 and ASTM A615/A615M-20. According to CRSI, members of ACI Committee 318 Subcommittee B, Anchorage and Reinforcement, recognize that the ACI 318-19 bar bend values do not comply with ASTM bend test requirements for Grades 80 and 100 and may need to be revised accordingly.

References

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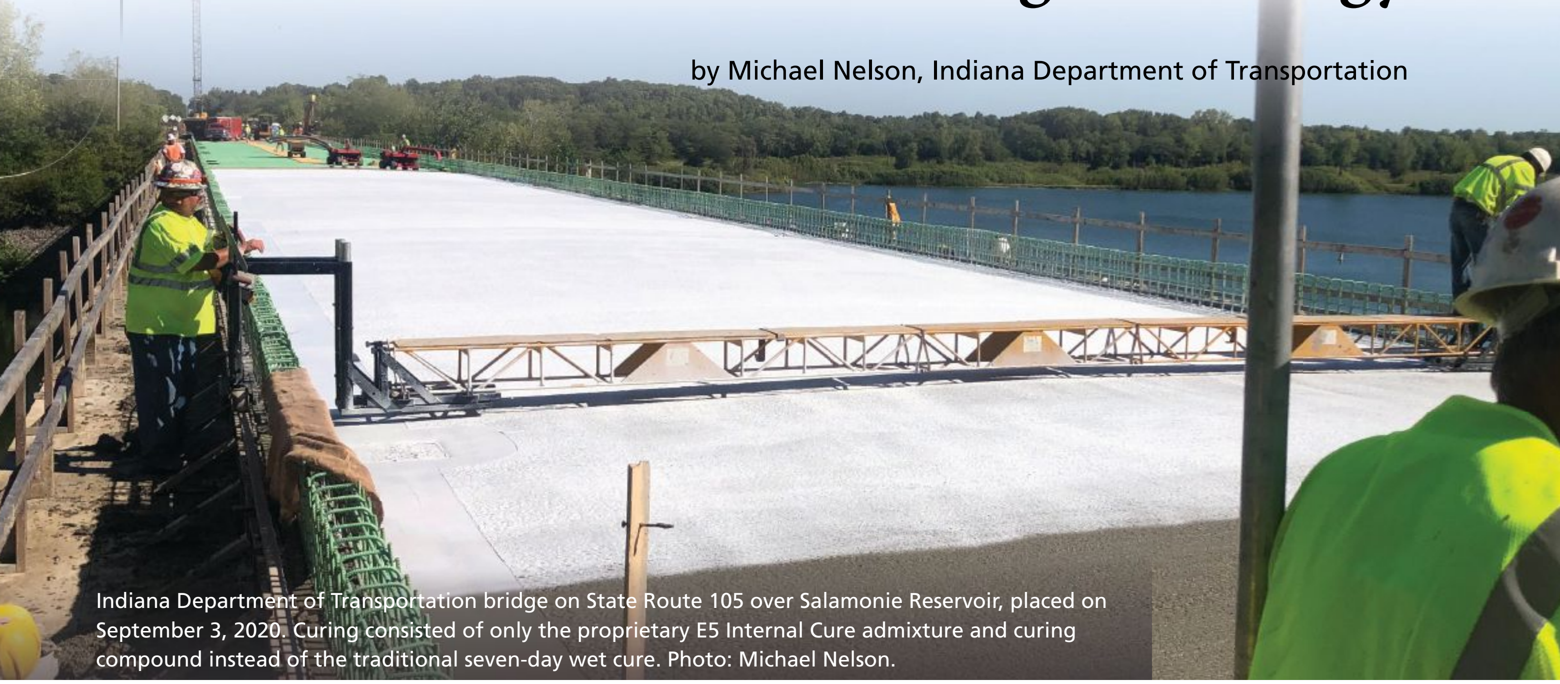
EDITOR'S NOTE

Contributions to the content of this article from CRSI vice president of engineering, Amy Trygestad, and others at CRSI are greatly appreciated.

The Indiana Department of Transportation Experiments with New Concrete Curing Technology

by Michael Nelson, Indiana Department of Transportation



Indiana Department of Transportation bridge on State Route 105 over Salamonie Reservoir, placed on September 3, 2020. Curing consisted of only the proprietary E5 Internal Cure admixture and curing compound instead of the traditional seven-day wet cure. Photo: Michael Nelson.

In 2020, the Indiana Department of Transportation (INDOT) began experimenting with a method for curing bridge decks that might be an alternative to the traditional seven-day wet cure. The method used only curing compound and an admixture called E5 Internal Cure manufactured by Specification Products in Noblesville, Ind. The E5 admixture is unique and has been shown to provide several benefits in commercial concrete work, including improved water retention, workability, finishability, and strength. INDOT has faced challenges in achieving timely and uniform curing when constructing bridge decks, and the admixture presented a low-risk option with potentially high rewards.

In June 2020, INDOT partnered with bridge contractor R. L. McCoy on an existing bridge contract that used standard INDOT bridge concrete by incorporating the E5 admixture and the new curing method. This project was an opportunity to begin changing the culture of concrete at INDOT, so a couple of other conditions were included in the concrete placement procedure. First, absolutely no water was allowed to be applied to the surface of the concrete for finishing purposes, including by laborers or the screed itself. Second, no evaporation retardants were to be used because these products are often used incorrectly as finishing aids. The deck placement went very smoothly, and everyone involved was optimistic about their observations. The concrete finished easily, and the laborers quickly learned that using water as a crutch for finishing was not needed. They also perceived a longer window for finishing. The bridge contractor, who is also a concrete pumping contractor, reported significantly lower pumping pressure than is normally seen with INDOT's bridge concrete mixtures. The concrete exhibited very little bleed water, and the curing compound was applied relatively quickly behind the screed, providing faster protection from the environment than is typically achieved when burlap and plastic are used. Word quickly spread about the success of the trial, and to date INDOT has placed 52 decks using the new curing method. The placements have involved 10 bridge contractors and six ready-mixed concrete companies.

The observations from the field have been consistent throughout all of the projects, and the improvements to general concrete practice were expected to provide benefits in overall concrete quality. With few exceptions, improved flexural strengths were seen. In April 2021, INDOT used a van equipped with a high-speed three-dimensional laser to inspect several of the decks. The concrete decks had minimal to no cracking, and that trend has continued with all the decks placed to date. Core samples were sent to Purdue University for analysis, and the concrete was found to be of good quality. However, the air-void system of the hardened concrete was less developed than expected when compared with the test results for the fresh concrete. Some autogenous shrinkage was also found. The conclusion was that the mixture needed more water and, perhaps the most critical finding to date, that concrete with E5 seems to thrive at a higher water–cementitious material ratio (*w/cm*) than is historically used for INDOT work. A *w/cm* between 0.44 and 0.48 seems to be ideal. There is still much to learn about this new technology, but the future is going to be exciting!

Michael Nelson is a concrete materials engineer with the Indiana Department of Transportation Division of Materials and Tests in Indianapolis.

EDITOR'S NOTE

Michael Nelson gave a presentation on this topic during the general session of the American Association of State Highway and Transportation Officials' Committee on Bridges and Structures Annual Meeting in 2021.

Making Precast Concrete Part of the Core Curriculum

by Dr. Mustafa Mashal, Idaho State University

Precast concrete has traditionally been the final lecture topic of reinforced concrete design courses. Many universities do not require a course in precast concrete or prestressed concrete, including both pretensioned and post-tensioned concrete designs, for an undergraduate (bachelor's) degree in civil engineering. However, bridge and precast concrete firms expect college graduates to be familiar with designing precast, prestressed concrete products such as double tees, beams, wall panels, culverts, and bridge girders. Engineers who have not been adequately exposed to the design, production, and installation of precast concrete elements have four options to choose from: learn precast concrete design on their own, ask their employer to assign someone to teach them precast concrete at work, convince their employer to not use precast concrete, or abandon their plan to work as a structural/bridge engineer and find another area of civil engineering to pursue. None of these options is beneficial to either the engineer or the employer.

One way to prepare students for a career in structural engineering including precast, prestressed concrete design is to have them take a semester-long course in precast concrete. In 2019, the PCI Foundation and the National Precast Concrete Association (NPCA) Foundation joined forces to fund a unique curriculum for precast concrete at Idaho State University (ISU) for four years. The precast concrete curriculum is the first studio jointly funded by the PCI and NPCA Foundations with a focus on transportation products such as bridges and culverts. ISU's Precast Concrete Engineering Studio is a three-credit-hour course that is offered every fall semester at the senior undergraduate and graduate levels. The studio has already been taken by 45 students and is a popular class. Many industry champions from across the nation have actively supported the studio and its growth.

The studio is very different from traditional design classes in civil engineering. It includes a variety of activities such as design lectures; visits to precast concrete production facilities; guest speakers; laboratory work and physical testing; introduction to complimentary PCI and NPCA resources; exposure to the latest technologies and materials such as ultra-high-performance concrete; participation in national PCI, NPCA, and American Segmental Bridge Institute (ASBI) student competitions; and opportunities to attend and present posters at the PCI Convention and The Precast Show. Some of the key activities for the class are discussed in the following sections.

Visits to Precast Concrete Plants

While it is common in traditional precast concrete courses to show videos and photos of how precast concrete elements are fabricated, students benefit much more from visits to actual precast concrete production facilities. When visiting in person, students can observe the whole process of how precast concrete elements are fabricated, cured, handled, and stored. The visits prepare students to identify the advantages and the limitations of precast concrete and give them an opportunity to directly interact with, listen to, and ask questions of the experts. The knowledge gained during a precast concrete plant tour will stay with the students for a lifetime. If they end up working in a bridge or structural engineering firm and a suitable project comes along, they might even consider proposing precast concrete for it. Furthermore, precast concrete yard personnel typically enjoy hosting students and faculty.

ISU is fortunate that several PCI and NPCA plants around the region have

Students pose during a plant tour, which is a key component of the Precast Concrete Engineering Studio at Idaho State University. The knowledge gained during a precast concrete plant tour will stay with the students for a lifetime. All Photos: Mustafa Mashal.

Students prepare concrete specimens for testing in the Idaho State University engineering materials laboratory.

always opened their doors for visits. Tours of precast concrete yards also build partnerships and collaboration between industry and academia on research, student competitions, and even internships.

Guest Speakers

To successfully prepare students for careers in precast concrete and bridge engineering, it is of utmost importance that the instructor teaching the class collaborate closely with industry champions. One effective way to help students learn about the state of the art for precast concrete is to invite speakers from the industry. Students always enjoy learning from industry experts about the practical aspects of what they are being taught in class and what they can expect as an engineer after graduating. Guest presentations also provide a chance for speakers to get to know students and consider them for future job opportunities in their firms.

Laboratory Work

Hands-on lab activities should be an integral part of teaching precast concrete. In most universities, it is a common practice to reserve structural laboratories primarily for research activities. However, all laboratories should be leveraged to teach precast concrete. Students will not only learn how to develop concrete mixtures and make precast concrete specimens; they will also learn how structural testing should be carried out in accordance with standards used in the precast concrete industry. Observations from testing and processing test data will remain with students far longer than the content of a purely theoretical lecture in the classroom.

Student Competitions

Participation in PCI, NPCA, ASBI, and other precast concrete and bridge-related competitions gives students opportunities to develop communication and hands-on skills, experience teamwork, practice technical writing, and network with industry leaders. For instance, there are some wonderful opportunities for students to take part in the PCI Convention and The Precast Show. In addition to the aforementioned benefits to the students, a competition can be a

Full-scale testing of a precast concrete pipe.

great venue for students to connect with future employers and peers from other institutions.

Conclusion

Precast concrete should be considered part of the core curriculum in civil engineering, especially for students who are interested in pursuing a career in bridge engineering. In addition to theoretical design lectures, innovative and hands-on activities are an important component of an effective precast concrete curriculum. Partnerships and collaboration with the precast concrete industry are essential for the success of the curriculum. A course such as ISU's Precast Concrete Engineering Studio can prepare students for rewarding careers in the precast concrete and bridge industries. Given the success of the studio, ISU faculty are planning to make it a permanent class in the civil engineering curriculum.

Students from Idaho State University's Precast Concrete Engineering Studio with their professor during a poster session at the 2020 PCI Convention at The Precast Show.

STATE

Iowa

by James Nelson and Ahmad Abu-Hawash, Iowa Department of Transportation

The reconstruction of this portion of the Missouri River levee system was designed to increase the conveyance of the river overflow by replacing an existing constriction with dual bridges. The project had an aggressive schedule as a result of severe flooding in the previous season. All Photos: Iowa Department of Transportation.

While some states have a conservative bent, the Iowa Department of Transportation (DOT) has been a leader with new technology. As the first state to experiment with ultra-high-performance concrete (UHPC), Iowa has a rich history of cutting-edge bridge design and construction.

Drawing on the success of those early UHPC beams in 2010, Iowa is working with the Federal Highway Administration (FHWA) and PCI to develop structural design specifications for UHPC. The lack of codified design practices has slowed the widespread usage of UHPC, and adoption of design specifications by the American Association of State Highway and Transportation Officials (AASHTO) could stimulate the use of UHPC with more optimized precast concrete beam shapes across the country.

Technology Transfer

The Iowa DOT has readily shared information on its use of UHPC in overlays and bridge connections as well as its success with accelerated bridge construction (ABC) techniques. It looks to expand the use of these tools, but the new methodologies have not been without their challenges. Although management is comfortable with taking acceptable risks, Iowa also relies on a strong system of independent checks and balances. Ultimately, the Iowa DOT is not taking risks with safety; it is taking risks with innovation.

Consider, for example, the use of UHPC for bridge deck overlays. The first project required remediation to address problems encountered from constructability issues, the use of new experimental techniques, and extreme weather conditions. However, subsequent projects took those lessons learned into account, and the most recent applications of UHPC overlays have been successful.

Like other states, Iowa outsources a fair amount of design work, but ABC lateral bridge slide projects were initially kept in house. After the Iowa DOT mastered lateral slide projects, the framework was established for consultants to design such projects as well. That enabled the Iowa DOT to work on improving the ABC tools in its arsenal. Contractors have also mastered these ABC techniques, and every lateral slide bridge project in the state, as well as all but one modular-unit ABC project, has met the critical closure time allotted.

To accommodate overflow from the Missouri River, the project team used 63-in.-deep, 155-ft-long precast concrete bulb-tee beams in all seven spans for the two 1100-ft-long bridges. To simplify and accelerate construction, all supports were zero skew. Use of the standard girder shape fast-tracked design, fabrication, and installation.

The Iowa Department of Transportation chose accelerated bridge construction methods to replace the Iowa Route 1 bridge over Old Woman's Creek south of Iowa City because replacement using traditional construction methods would have required vehicles to detour 19 miles. The contractor constructed the single-span, 135-ft-long, 44-ft-wide precast, prestressed concrete beam bridge adjacent to its final location and then used the lateral slide technique to meet the 45-day closure period. The project incorporated lessons learned from earlier lateral slide projects and also used ultra-high-performance concrete to complete superstructure-to-substructure connections for the integral abutments.

Massena Lateral Bridge Slide

Iowa started constructing ABC projects consisting mainly of precast concrete elements and modular units in the early 2000s, but it was not until 2012 that the Iowa DOT began working with the FHWA to demonstrate the use of the lateral bridge slide technique coupled with prefabricated bridge element systems. The Massena lateral bridge slide constructed in 2013 was the first use of this technology in Iowa. The project to replace the existing bridge on Iowa Route 92 in southwestern Iowa minimized traffic impact with a nine-day critical closure and enhanced construction zone safety by building the new bridge superstructure away from traffic.

The Iowa DOT subsequently completed five lateral bridge slide projects and has additional projects included in its highway program. Iowa considers the lateral bridge slide technique to be cost-effective for projects that traditionally required a temporary bridge and for those with long detours.

Industry Partnerships

Industry associations are a powerful ally for owner agencies seeking to improve bridge design and construction practices. The Iowa DOT has a long-standing partnership with the state's chapter of the Associated General Contractors of America and meets with chapter members routinely to discuss pilot projects, new details, and other industry innovations. Both road and bridge bureaus have collaborated on the use of building information modeling (BIM) and three-dimensional (3-D) modeling for future project delivery. This engagement is critical to the implementation of research and development efforts.

The Iowa DOT recently made the switch to 3-D bridge design and Bentley Systems Connect. Going forward, a 3-D bridge model will be attached to each project, which makes the DOT's collaboration with industry groups critical. The end goal is a digital as-built model for use in asset management and the agency is working to define those deliverables.

Applying lessons learned from the Massena Bridge project, the second lateral slide bridge was performed for the Iowa Route 1 Bridge over Camp Creek. The project used accelerated bridge construction methods, as the new bridge was constructed just east of the existing bridge and then slid into place.

Digital As-Builts

As an early adopter of new technology, the Iowa DOT is actively engaged with the AASHTO Technology and Software Committee, which is leading the effort for widespread use of BIM for bridges. Working with almost half of the state DOTs and the FHWA, the committee is charged with developing a national standard for open exchange of bridge and structure data using the Industry Foundation Classes schema. This model-based approach will encompass every phase from planning and design through fabrication, construction, and asset management.

The lack of national standards for BIM is holding the bridge industry back as compared with the building industry. Efforts to develop a unified framework for digital twin applications involve cooperation from concrete industry organizations such as the National Concrete Bridge Council, the American Segmental Bridge Institute, PCI, and others. (For more information on digital twins, see the Summer 2021 and Fall 2021 issues of *ASPIRE*®.)

To synchronize the digital model and the bridge, all stakeholders need to populate the model with data throughout its life cycle. The Iowa DOT foresees the long-term benefits of seamless integration, from avoiding conflicts in construction through asset management.

Safety and Mobility

Like many other states, Iowa frequently uses deicing salts to keep roads clear. The chlorides in these salts wreak havoc on the long-term durability of bridges. Maintaining the infrastructure system in a state of good repair requires a tremendous investment. There are many aging structures in Iowa's inventory, with

The precast, prestressed concrete beams for the Iowa Route 1 Bridge over Camp Creek are set on temporary falsework to construct the bridge superstructure off alignment. There are stainless steel slide shoes under the beams for the lateral slide of the new 120-ft-long, 44-ft-wide bridge.

bridges built in the 1960s and 1970s accounting for more than one-third of Iowa's primary system bridge inventory.

The Iowa DOT takes a three-pronged approach to maintaining the state's bridge assets. The first prong is an increased emphasis on bridge stewardship, balancing the need for bridge replacement with the need for capacity improvement. The second is to keep structures in good repair longer through active bridge preservation activities such as bridge deck overlays and bridge joint repairs. The third is a commitment to constructing robust bridges with excellent materials and smart, robust details. That investment in service-life design will pay off with modern, longer-lasting structures.

To support this approach, the agency is investigating service-life design concepts to minimize maintenance for 50 years. Currently, the average age of bridges at replacement is less than 65 years. The long-term goal is to consistently achieve a typical service life of 75 years for most bridges on the primary system and enhanced service life of 100 years for major structures, especially those over the Missouri and Mississippi Rivers.

Iowa Highway 2 Overflow Bridges

Historic flooding along the Missouri River in 2019 brought the need for flood relief, recovery, and mitigation to the forefront. The Iowa Highway 2 crossing at the Missouri River was identified as a pinch point constricting the flow of the Missouri River and the levee system. The Iowa DOT was challenged to deliver bridges that would accommodate the overflow of the river before the flood season of 2020. The agency needed to ensure that dual seven-span, 1100-ft-long precast concrete beam bridges would be designed and constructed in record time.

A drone-captured image of the ultra-high-performance concrete (UHPC) bridge deck overlay process in Jasper, Iowa. To extend the life of the existing bridge, a thin layer of UHPC was placed on the deck as a protective layer, sparing the expense of deck repair and full deck replacement. The Iowa Department of Transportation readily shares information on its use of UHPC in overlays.

The goal was to open the bridges to traffic by March 1, 2020. Notices to proceed on preliminary and final designs were awarded simultaneously on April 30, 2019, in an integrated contract approach that expedited the project. The bridges were designed in just nine weeks, which meant that most of the construction work could be completed before harsh winter weather arrived. The first bridge was open to traffic just six months after letting.

The decision to use standard Iowa bulb-tee beams was the key to fostering speed of design, fabrication, and construction. Because 63-in.-deep, 155-ft-long precast concrete bulb-tee beams (BTE 155) were used for all seven spans of each bridge, engineers could move quickly through beam design, the fabricator had the forms available, and the contractor was familiar with placement. For this accelerated project, standard precast concrete beams were the only viable option.

Using a standardized design may not seem innovative, but the creative decision to do so allowed the team to meet every critical deadline. This precast concrete project was completed in about half the time that a steel construction project would have required. ABC techniques frequently focus on the construction phase, but in this case, the Iowa DOT found a way to accelerate the entire delivery process.

Looking to the Future

Following the 10th anniversary of Iowa DOT using the first UHPC girders for a bridge in North America, Iowa is looking to the future AASHTO specifications for the structural design of UHPC members. Such new specifications are the key to innovative solutions, especially for increasing girder span-to-depth ratios. Significant savings may be achieved for replacement bridges over waterways where the hydraulic opening size must be increased. A longer, shallower beam could reduce costs for raising grades and acquiring rights-of-way, and potentially provide substructure savings as well.

The Iowa DOT's efforts with BIM and digital as-builts should enhance the efficiency of the design process and improve the quality of designs. The result will be the optimized design of materially efficient, high-performance, long-lasting concrete bridges.

James Nelson is the director and Ahmad Abu-Hawash recently retired as the chief structural engineer of the Bridges and Structures Bureau for the Iowa Department of Transportation.

Effects of Truck Platooning on Bridges

by Dr. Lubin Gao, Federal Highway Administration

Connected and autonomous vehicle technology is advancing both in the United States and abroad. In applications with commercial trucks, the technology is normally referred to as "truck platooning technology." Trucks enabled with this technology can communicate and synchronize with each other and travel closely together in a platoon. The technology offers the potential benefits of improved traveling safety and efficiency, but the concentration of more loading over short distances may adversely affect the safety and long-term serviceability of the highway bridge network. It is important to investigate these potential impacts.

In August 2018, the Federal Highway Administration (FHWA) initiated a project to study the impacts of truck platooning on the structural safety of bridges from the strength limit state perspective.[1]

Literature Review

The research started with a literature search. Although many publications on truck platooning technology were identified, most past work has focused on the development of the technologies, operational issues, and fuel economy. At the time of the literature review, no studies on the effects of truck platoons on bridges were found.

Representative Trucks and Truck Platoon Configurations

A review of weigh-in-motion data from 10 states showed that the most common truck class is FHWA Class 9, a five-axle single-trailer truck (**Fig. 1**). Taking into account long-haul commercial truck traffic on the Interstate System (IS), the National Highway System (NHS), and the National Truck Network (NN), together with the Class 9 truck statistics, a representative model of the most common trucks was selected. This "typical" truck (**Fig. 2**) is a five-axle tractor-semitrailer combination that falls within the truck size and weight limits operating on the IS as set forth in 23 U.S. Code §127(a) and 23 Code of Federal Regulations (CFR) §658.17(b)-(e).

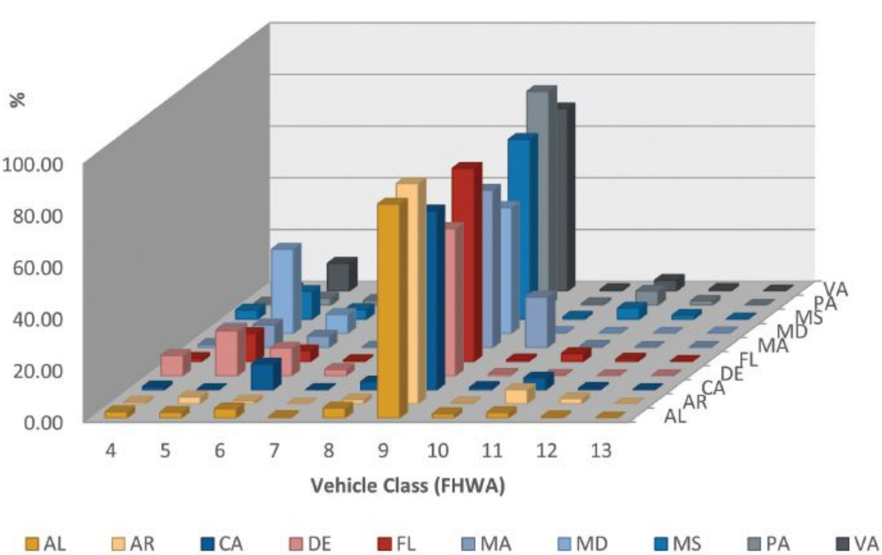


Figure 1. Vehicle class distributions from a review of weigh-in-motion data from 10 states. The bar chart shows the percentage of all vehicles with a gross vehicle weight equal to or greater than 20 kip for each vehicle class in a given state. Figure: Federal Highway Administration (FHWA), Figure 2 from *Truck Platooning Impacts on Bridges: Phase I—Structural Safety*.

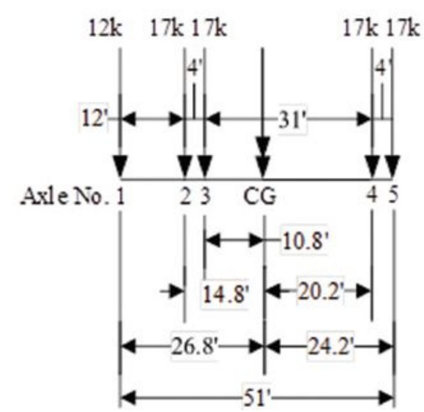


Figure 2. Schematic of axle configuration for a "typical" truck (5-axle, 40-ton truck) used in analyses. Figure: Federal Highway Administration, Figure 11 from *Truck Platooning Impacts on Bridges: Phase I—Structural Safety*.

In addition, two types of American Association of State Highway and Transportation Officials (AASHTO) trucks, Type 3S2 and Type 3-3, were also included in the study. (These types are from AASHTO's *The Manual for Bridge Evaluation*,[2] which is incorporated by reference in 23 CFR §650.317.)

Truck platoons consisting of two, three, and four trucks of the selected truck type with spacings of 30, 50, and 70 ft were included in the study (**Fig. 3**). The spacing was measured from the rear axle of a truck to the front axle of the following truck. In total, 30 different platoon configurations were considered in the analyses.

Bridge Spans and Load Effects

Representative bridge span configurations were selected to determine the load effects from the platoon configurations and AASHTO HL-

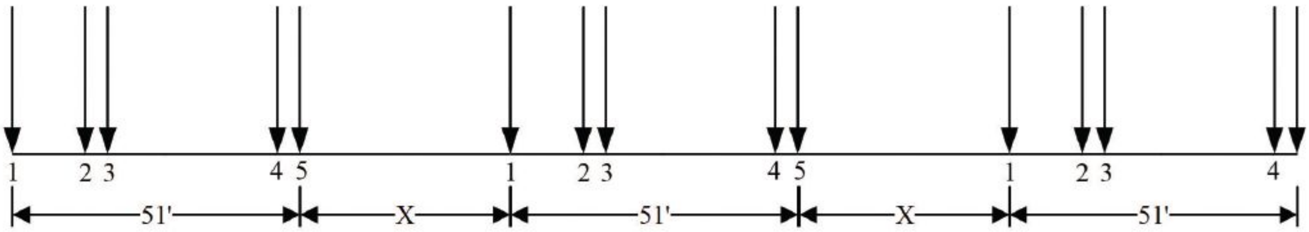


Figure 3. Schematic of axle configurations for a "typical" three-truck platoon. Platoons with X = 30, 50, and 70 ft were analyzed in the study. Figure: Federal Highway Administration, Figure 16 from *Truck Platooning Impacts on Bridges: Phase I—Structural Safety*.

93 and HS-20 design loads. The selected span lengths ranged from 30 to 300 ft.

Load effects at critical sections in simple spans, two equal continuous spans, and three equal continuous spans were considered. For example, the analysis included maximum positive moment in span 1, maximum negative moment at the intermediate support, maximum end shear, and maximum shear on one side of the intermediate support for two equal continuous spans.

The truck platoons were treated as actual vehicles, which means that all axles were considered, regardless of whether they increased or decreased the load effect.

Strength Analysis of Existing Bridges

Data from the 2018 National Bridge Inventory (NBI)[3] were used in this study. The controlling rating factor for each platoon configuration was determined based on load effect ratio, live load factor ratio, and the operating rating factor of design load recorded in the NBI database (item 64). Truck platoons were rated at the operating rating level with the load factor rating (LFR) method or the legal load rating level with the load and resistance factor rating (LRFR) method.

Bridges that have a load rating factor lower than 1.0 for a particular truck platoon configuration were considered to have insufficient structural capacity at the strength limit state to carry the truck platoon. **Table 1** lists the number of bridges with a platoon operating rating factor less than 1.00 on the IS, NHS, and NN for the entire country. The numbers exclude bridges currently having an operating rating factor less than 1.00 for the HL-93 design load using the LRFR method or an operating rating factor less than 1.0 for the HS-20 design load using the LFR method. The data in Table 1 show that 0.9%, 1.4%, and 1.6% of all bridges on the IS, NHS, and NN, respectively, have an operating rating factor less than 1.0 for the truck platoons with a truck spacing of 30 ft with two, three, or four semitrailer trucks, respectively. Altogether, 98.4% of bridges on the three highway systems have adequate capacity to carry the truck platoon configurations investigated in this research.

Table 1. Number of bridges with a platoon operating rating factor less than 1.0

	Interstate System	National Highway System	National Truck Network	Total for the three systems
Total number of bridges on each system	57,640	145,190	102,707	163,292
Loading	Number of bridges with operating rating factor <1.00			
Single truck	0	0	0	0
2 trucks at 30 ft spacing	378	1239	853	1468
2 trucks at 50 ft spacing	141	420	278	497
2 trucks at 70 ft spacing	30	64	43	70
3 trucks at 30 ft spacing	701	2006	1382	2309
3 trucks at 50 ft spacing	190	562	377	652
3 trucks at 70 ft spacing	37	80	54	85
4 trucks at 30 ft spacing	817	2265	1542	2583
4 trucks at 50 ft spacing	196	575	383	665
4 trucks at 70 ft spacing	40	84	57	89

Note: Numbers exclude bridges currently having an operating rating factor less than 1.00 for the AASHTO HL-93 or HS-20 design load. Values listed in the right column account for the fact that some bridges are included in more than one of the systems and should not be counted more than once for the total value of the three systems. Table created by the Federal Highway Administration based on 2018 National Bridge Inventory data.[3]

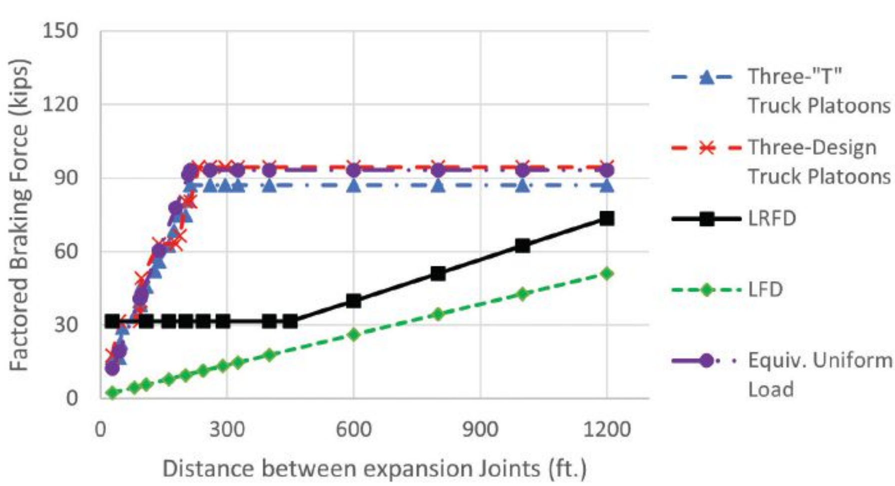


Figure 4. Factored braking force from three-truck platoons. Figure: Federal Highway Administration, Figure 38 from *Truck Platooning Impacts on Bridges: Phase I—Structural Safety*.

Other Truck Platooning Loads on Bridges

Based on a review of other studies, the FHWA project[1] found that a reduced dynamic allowance of 20% may be applied to the entire platoon because the interaction between the trucks in a platoon results in a smaller impact factor than for a single truck. For shorter spans where only one truck can fit on the structure, the AASHTO design loads with the 33% dynamic allowance applied to the truck will continue to control the design over the 20% for the platoon.

In addition to gravity effects, live loads produce, or are subject to, three additional load components: braking force (**Fig. 4**), centrifugal force, and wind load on live loads. These other load components mainly affect the design of the bearings, substructures, and foundations.

Service and Fatigue Limit States

The FHWA study's final report[1] offers a brief discussion of possible truck platooning effects on service and fatigue limit states. A list of bridge components that may be controlled by the service limit state and the possible effects of truck platoons on these components is presented.

Truck platoons may cause some details currently classified as having infinite fatigue life to be reclassified as having finite fatigue life. Depending on the bridge span length and configuration, the presence of platoons may increase the number of higher-stress cycles and affect the remaining life of details.

Closing Remarks

This study investigated the effects of truck platooning on bridges on main highway systems—the IS, NHS, and NN—at the strength limit state.

The study found that some configurations of truck platoons can produce load effects greater than those from the standard design loads at an operating rating or legal load evaluation level. The bridges potentially affected by the platoon configurations (Table 1) are bridges with longer spans. Further detailed structural evaluation will need to be performed to confirm the adequacy of the structural capacity of those bridges. The study also concluded that bridge superstructures having an inventory rating factor greater than 1.0 for HL-93 loading will have adequate capacity to carry the truck platoons investigated.

Additional research is warranted to assess other impacts of truck platoons, which may include performing statistical live load analysis of platoons, establishing appropriate dynamic load allowance applicable to truck platoons, and establishing the effect of truck platoons on the fatigue life and service limit state of bridges.

References

1. Wassef, W. 2021. *Truck Platooning Impacts on Bridges: Phase I—Structural Safety. Final Report*. FHWA-HIF-21-043. Washington, DC: Federal Highway Administration (FHWA). https://www.fhwa.dot.gov/bridge/loadrating/pubs/hif21043.pdf.
2. American Association of State Highway and Transportation Officials (AASHTO). 2018. *The Manual for Bridge Evaluation*. 3rd ed. Washington, DC: AASHTO.
3. FHWA Office of Bridges and Structures. 2019. "National Bridge Inventory: 2018 Data (updated 4/22/19)." https://www.fhwa.dot.gov/bridge/nbi/ascii.cfm.

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

IN THIS ISSUE

http://www.aspirebridge.com/magazine/2017Fall/Project-RapidRiseFromTheAshes.pdf
In 2017, when a massive fire erupted beneath the heavily traveled Interstate 85 through Atlanta, Ga., and several spans along the viaduct collapsed, the Georgia Department of Transportation immediately contacted C.W. Matthews Contracting Co. (CWM) for help. CWM is featured in the Focus article on page 6. This link accesses the Project article in the Fall 2017 issue of *ASPIRE*®, which gives details of the six-week rebuilding project.

https://www.nps.gov/gwmp/learn/management/amb-rehabilitation.htm
The rehabilitation of the Arlington Memorial Bridge in Washington, D.C., is featured in a Concrete Bridge Preservation article on page 34. This link accesses a National Park Service webpage with photos, a time-lapse video, and history of the rehabilitation project.

https://iowadot.gov/massenabridge
To replace the Massena Bridge on State Route 92, the Iowa Department of Transportation used a lateral bridge slide, and the installation was completed during a nine-day closure period. This link accesses a website with photos, construction plans, lessons learned, and videos of the accelerated bridge construction project. Iowa is featured in the State article on page 54.

https://www.youtube.com/watch?v=NA-nhOMEn8s
This animated video produced by the Iowa Department of Transportation shows the steps of the 2013 Massena Bridge replacement project. Iowa is featured in the State article on page 54.

https://www.asbi-assoc.org/index.cfm/resources/videos
This American Segmental Bridge Institute (ASBI) webpage provides links to numerous videos on the construction, grouting, inspection, and maintenance of concrete segmental bridges. Segmental bridges are the focus of the Concrete Bridge Preservation article on page 28.

https://www.asbi-assoc.org/index.cfm/events/MonthlyWebinars
This is a link to the ASBI archive of their monthly webinar series on topics such as "Repair and Maintenance of Post-Tensioned Concrete Bridges." Segmental bridges are the focus of the Concrete Bridge Preservation article on page 28.

http://www.trb.org/Publications/Blurbs/181972.aspx
Segmental bridges are the focus of the Concrete Bridge Preservation article on page 28. The recently published National Cooperative Highway Research Program Synthesis 562: *Repair and Maintenance of Post-Tensioned Concrete Bridges* includes a literature review, the results of a survey distributed to 50 state departments of transportation, current practices used by bridge owners to repair and maintain post-tensioned bridges, and lessons learned. The report can be downloaded via this link.

http://www.aspirebridge.com/magazine/2021Summer/CCC-ThreadingANeedle.pdf
The Project article on page 24 features a five-unit, 14-span, 1855-ft-long prestressed concrete girder bridge on Interstate 20 near Jackson, Miss. The structure includes a 170-ft span over a railroad with limited access. The contractor developed self-propelled modular transports (SPMTs) with a gantry system to erect the 200,000-lb girders. This link accesses a Creative Concrete Construction article describing SPMTs and the erection process from the Summer 2021 issue of *ASPIRE*.

https://www.fhwa.dot.gov/bridge/loadrating/pubs/hif21043.pdf
The FHWA article on page 58 is based on the Federal Highway Administration report *Truck Platooning Impacts on Bridges: Phase I–Structural Safety* (FHWA-HIF-21-043). The report can be downloaded via this link.

http://www.aspirebridge.com/magazine/2019Summer/FHWA-TruckPlatoonsAndHighwayBridges.pdf
The FHWA article on page 58 explores the effects of truck platooning on bridges. This link accesses an FHWA article in the Summer 2019 issue of *ASPIRE* that describes the truck-platooning concept.

https://www.pci-foundation.org
The Professor's Perspective article on page 52 describes the precast concrete curriculum at Idaho State University. The studio concept for precast concrete education was developed by the PCI Foundation. This website showcases activities of various studios at universities across the country and gives access to educational aids for all instructors interested in precast concrete.

https://cshub.mit.edu/buildings/lca
The Perspective on page 10 discusses how life-cycle assessments can be an important tool in moving toward carbon neutrality for concrete structures. This is a link to the life-cycle assessment webpage on the Massachusetts Institute of Technology Concrete Sustainability Hub website. The page contains links to news, research, and webinars relating to life-cycle assessment.

http://www.aspirebridge.com/magazine/2020Summer/CBT-UsingEmbeddedCorbels.pdf
The Sargent Beach Bridge is featured in a Project article on page 18. The bridge used a spliced girder to span 300 ft, and the drop-in girder was temporarily supported by embedded steel corbels. This concept was also used on the Phoenix Sky Harbor Airport's Sky Train bridge. Details of that project are described in a Concrete Bridge Technology article in the Summer 2020 issue of *ASPIRE*. This is a link to download the article.

https://www.post-tensioning.org/Portals/13/Files/PDFs/Events/Conventions/TechnicalSessions/2016/042516Reese.pdf
The Sargent Beach Bridge, which is featured in a Project article on page 18, uses spliced, precast concrete girders to span 300 ft. This is a link to slides from a 2016 PTI Convention presentation on the state-of the-art of spliced, precast concrete girder bridges.

Details on Several Upcoming Changes to the *AASHTO LRFD Bridge Design Specifications*: Deflection Calculations and Stress Limits

by Dr. Oguzhan Bayrak, University of Texas at Austin

My article in the Fall 2021 issue of *ASPIRE*® summarized 11 working agenda items prepared by the American Association of State Highway and Transportation Officials (AASHTO) Technical Committee for Concrete Design (T-10) that were adopted by the AASHTO Committee on Bridges and Structures (COBS) at its summer 2021 meeting. This article focuses on two of those items and provides technical details for our readership.

Working Agenda Item 133: Deflection and Camber Calculations

According to the newly revised provisions of Article 5.6.3.5.2 in the *AASHTO LRFD Bridge Design Specifications*,[1] deflection and camber calculations are to consider appropriate combinations of dead load, live load, prestressing forces, erection loads, concrete creep and shrinkage, and steel relaxation. Revised provisions for both instantaneous and time-dependent deflections are forthcoming to improve the accuracy of the predicted deflections, as discussed in the following sections.

Instantaneous Deflections

The calculation of the effective moment of inertia will be updated to improve the accuracy of instantaneous deflection calculations. Unless obtained by a more comprehensive analysis, instantaneous deflections for nonprestressed concrete members are to be calculated using the modulus of elasticity for concrete as specified in Article 5.4.2.4, and the effective moment of inertia I_e calculated in accordance with **Table 1**.

Table 1. Effective moment of inertia I_e from the newly adopted AASHTO LRFD Table 5.6.3.5.2a-1

Service moment	Effective moment of inertia I_e, in.[4]
$M_a \leq \frac{2}{3} M_{cr}$	I_g
$M_a > \frac{2}{3} M_{cr}$	$\dfrac{I_{cr}}{1-\left(\dfrac{\frac{2}{3}M_{cr}}{M_a}\right)^2\left(1-\dfrac{I_{cr}}{I_g}\right)}$

Note: The cracking moment is calculated as $M_{cr} = \dfrac{f_r I_g}{y_t}$.

f_r = modulus of rupture of concrete as specified in Article 5.4.2.6 (ksi); I_{cr} = moment of inertia of the cracked section, transformed to concrete (in.^{4}); I_g = moment of inertia of the gross concrete section about the centroidal axis, neglecting the reinforcement (in.^{4}); M_a = maximum moment in a component due to service loads at the stage for which deformation is computed (kip-in.); M_{cr} = cracking moment (kip-in.); y_t = distance from the centroidal axis of the gross section to the extreme fiber in tension (in.).

For prismatic members, the effective moment of inertia is taken as the value obtained from Table 1 at midspan for simple or continuous spans, or at the support for a cantilever. For continuous, nonprismatic members, the effective moment of inertia is the average of the values obtained from Table 1 for the critical positive and negative moment sections.

For prestressed concrete members meeting the tensile stress limits of Article 5.9.2.3.2b, a provision stating that instantaneous deflections for such members may be calculated based on the moment of inertia of the gross concrete section I_g has been added.

Time-Dependent Deflections

An updated multiplier for estimating time-dependent deflections will be incorporated into the provisions to improve the accuracy of deflection predictions. Unless obtained from a more comprehensive analysis, additional time-dependent deflection for nonprestressed concrete members resulting from creep and shrinkage of flexural members is calculated as the product of the immediate deflection caused by sustained load and the multiplier used for calculating additional time-dependent deflection λ_Δ:

$$\lambda_\Delta = \frac{\xi}{1+50\rho'}$$

where

$$\rho' = \frac{A'_s}{bd}$$

A'_s = area of compression reinforcement (in.^{2})

b = width of compression face of member (in.)

Table 2. Time-dependent factor for sustained loads from the newly adopted AASHTO LRFD Table 5.6.3.5.2b-1

Sustained load duration (months)	Time-dependent factor ξ
3	1.0
6	1.2
12	1.4
60 or more	2.0

d = distance from the extreme fiber in compression to centroid of longitudinal tension reinforcement (in.)

ξ = time-dependent factor in accordance with **Table 2**

The quantity ρ' is calculated at midspan for simple or continuous spans, or at the support for a cantilever.

Additional time-dependent deflection of prestressed concrete members is calculated considering stresses in concrete and reinforcement under sustained load, and the effects of creep and shrinkage of concrete and relaxation of prestressing reinforcement.

Working Agenda Item 200: Compressive and Tensile Stress Limits

This approved working agenda item clarifies language in a number of different locations within the specifications. Broadly, the terminology is being revised to read "effective prestress," and the terms "after losses" and "before losses" have been eliminated because some type of prestress loss is always present in prestressed concrete elements. Prestressed concrete members first experience elastic shortening; over time, relaxation of strands and creep and shrinkage of concrete all influence the effective prestress.

Article 5.9.2.3.1a—Compressive Stresses—is being revised to provide relief in the following specific, temporary stress conditions. The compressive stress limit for pretensioned and post-tensioned concrete components, including segmentally constructed bridges, is limited to $0.65f'_{ci}$, except when lateral bending due to tilt, wind, or transportation-induced centrifugal force is explicitly considered. In these temporary stress conditions, the compressive stress limit at the component extremities is permitted to be increased to $0.70f'_{ci}$. These stress limits also apply to temporary preservice load stages, such as lifting, hauling, and erection, with concrete strength at the time of loading substituted for f'_{ci} in the stress limits.

Temporary tensile stress limits for concrete bridges other than segmentally constructed bridges are clarified in **Table 3**.

Bonded reinforcement sufficient to resist the tensile force in the concrete is to be located as close to the tension face of the member as possible. This reinforcement must be located on the tension side of the neutral axis. When the depth to the neutral axis from the tension face of the member is less than the concrete cover specified in Article 5.10.1, the reinforcement at a depth equal to the clear cover can be assumed to resist the tension force in the concrete for the purpose of determining the appropriate tensile stress limit in Table 3.

At sections located less than the development length from the end of the reinforcement provided to resist the tensile force in the concrete, the area of reinforcing steel A_s used in design is to be reduced in proportion to the lack of full development.

In future articles, additional changes to the AASHTO LRFD specifications will be discussed in an effort to keep our readership informed of the upcoming changes that will be included in the next edition of the specifications, which is to be published in 2023.

Reference

1. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications*, 9th ed. Washington, DC: AASHTO.

Table 3. Revised temporary tensile stress limits in prestressed concrete in AASHTO LRFD Table 5.9.2.3.1b-1

	Location	Stress limits, ksi
Other than segmentally constructed bridges	Areas with bonded reinforcement (reinforcing bars or unstressed prestressing strand) sufficient to resist the tensile force in the concrete computed assuming an uncracked section, where reinforcement is proportioned using a stress of $0.5f_y$, not to exceed 30.0 ksi	$0.24\lambda\sqrt{f'_{ci}}$
	All other areas	$0.0948\lambda\sqrt{f'_{ci}} \le 0.2$
	For handling stresses in prestressed piles	$0.158\lambda\sqrt{f'_{ci}}$

Note: f'_{ci} = specified concrete compressive strength at time of transfer of prestressing force or application of loading (ksi); f_y = specified minimum yield strength of reinforcement (ksi); λ = concrete density modification factor.