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EDITORIAL

Photo: PCI.

Expand the Foundational Base in Our Profession

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

The last quarter of 2017 was a particularly busy time, with many great engineering conferences and meetings. I noticed strong attendance and participation at the fall engineering forums (such as the Western Bridge Engineers' Seminar, New York City Bridge Conference, PCI's Committee Days, ASBI Annual Conference, National Concrete Bridge Council meetings, and National Accelerated Bridge Construction Conference). The two overarching themes at these venues were to encourage technical exchanges and rekindle friendships. Both themes are so important. Therefore, in this editorial, I want to build upon an idea that Chuck Prussack, the 2016 PCI chairman of the board, included in his annual message published in the January-February 2016 issue of *PCI Journal*: "Stewardship Key to Future."

Very often, we learn and we share with each other at these events. Two years ago, I saw a materials scientist present data and observations/findings with recommendations about a particular industry problem. His ideas seemed overstated, and some discussion of them took place at the time of the presentation. Twelve months later, in the published paper, this researcher provided conclusions about a bridge system that, from the perspective of a bridge engineer, did not seem logically connected or even based on the study's findings. In my opinion, the author overstepped his area of expertise and the paper's editors and reviewers may have slipped as stewards.

These types of miscues can detract from the value of research findings. In this case, the paper outlined several important issues: key specifications that were violated or missed; inspection opportunities that were skipped by the contractor and his quality control team; and stop-and-hold points totally missed by the construction engineering and inspection inspectors for the owner. In the Winter 2017 issue of *ASPIRE*®, we published an editorial titled "Responsibility, Authority, and Accountability" (RAA), which emphasized that improved materials cannot be the only aspect of successful projects. Unfortunately, at the same time that *ASPIRE* was promoting this approach, the paper by the materials science researcher demonstrated that not every study meets the RAA standards.

As I attended recent fall events, it was encouraging to learn about and debate so many great concrete bridge solutions. Then again, I was with good stewards of our industry. Now, those of us who participated in these meetings have an opportunity to continue our stewardship. Here is what I ask of attendees: Take time for an internal lunch-and-learn with your firm. Share with your coworkers what you saw and discussed. And, yes, do your homework—make an extra effort to verify data from papers and presentations, instead of accepting the conclusions of peer-reviewed research over the best practices and manuals of an industry.

Share with your coworkers what you saw and discussed.

Industry-balloted, consensus committee documents and standards represent the conclusions of a diverse mix of industry professionals, not just the few peer reviewers who typically comment on a research article. This diversity ensures that every perspective is considered and best practices are identified in a comprehensive and balanced manner. Going forward, let's also increase the ranks of our profession's stewards. If every firm is represented by at least one person at professional events, we can broaden the foundational base in our profession.

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The Lesner Bridge in Virginia Beach, Va., consists of twin precast concrete segmental concrete bridges erected by span-by-span and balanced-cantilever methods. Photo: RS&H.

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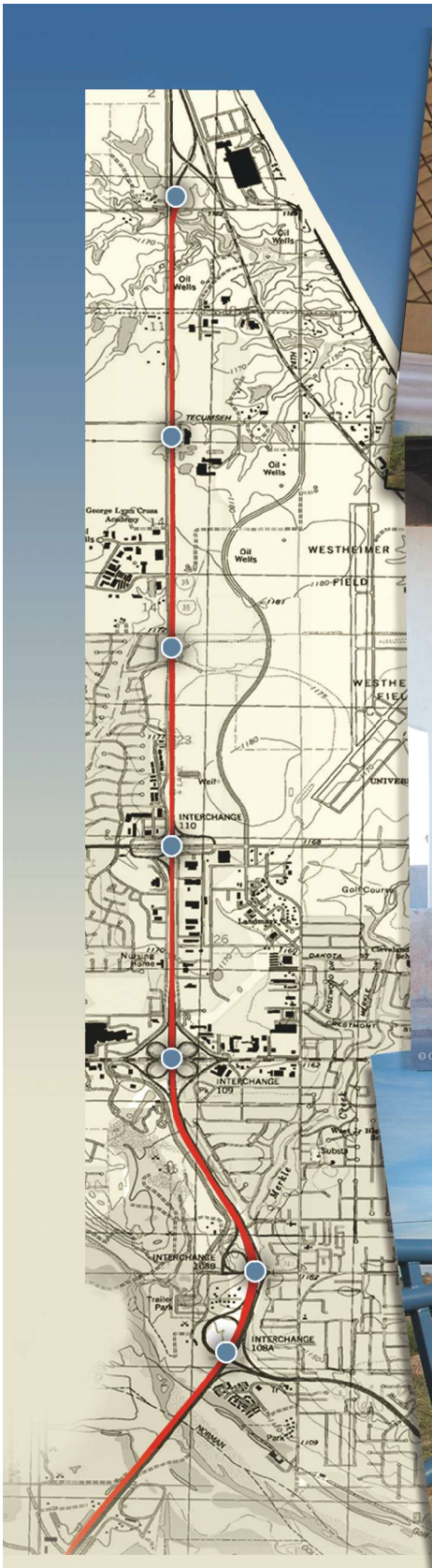

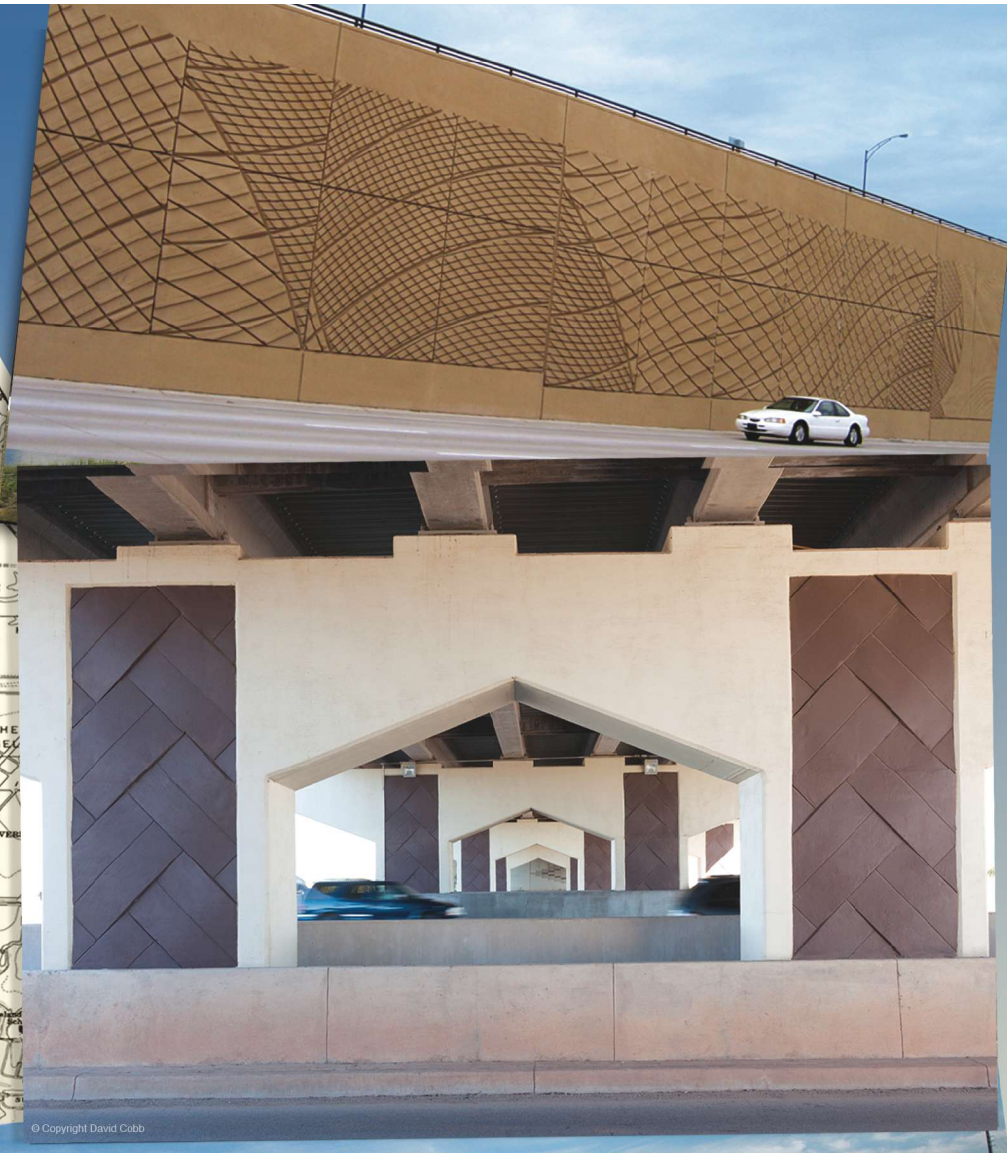

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CONCRETE CALENDAR 2018–2019

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

January 7–11, 2018
Transportation Research Board 97th Annual Meeting
Walter E. Washington Convention Center
Washington, D.C.

January 22–26, 2018
World of Concrete 2018
Las Vegas Convention Center
Las Vegas, Nev.

February 20–24, 2018
PCI Convention and National Bridge Conference
Colorado Convention Center
Denver, Colo.

March 21–23, 2018
2018 DBIA Design-Build in Transportation Conference
Oregon Convention Center
Portland, Ore.

March 25–29, 2018
ACI Spring 2018 Convention
Grand America & Little America Hotels
Salt Lake City, Utah

April 9, 2018
ASBI 2018 Grouting Certification Training
J.J. Pickle Research Center
Austin, Tex.

May 6–10, 2018
2018 PTI Convention
Minneapolis Hilton
Minneapolis, Minn.

June 11–14, 2018
International Bridge Conference
Gaylord National Resort & Convention Center
National Harbor, Md.

June 25–28, 2018
AASHTO SCOBS Meeting
Double Tree by Hilton Burlington
Burlington, Vt.

October 6–12, 2018
fib Congress 2018
Melbourne, Australia

October 14–18, 2018
ACI Fall 2018 Convention and Exposition
Rio All-Suites Hotel and Casino
Las Vegas, Nev.

October 10–13, 2018
PCI Committee Days and Membership Conference
Loews Chicago O'Hare Hotel
Rosemont, Ill.

November 6–7, 2018
ASBI 29th Annual Convention
Loews Chicago O'Hare Hotel
Rosemont, Ill.

February 26–March 2, 2019
PCI Convention and National Bridge Conference
Louisville, Ky.

March 24–28, 2019
ACI Spring 2019 Convention
Quebec City Convention Centre and Hilton Quebec
Quebec City, QC, Canada

June 2–5, 2019
2nd International Interactive Symposium on Ultra-High-Performance Concrete
Hilton Albany
Albany, N.Y.

October 2–5, 2019
PCI Committee Days and Membership Conference
Loews Chicago O'Hare Hotel
Rosemont, Ill.

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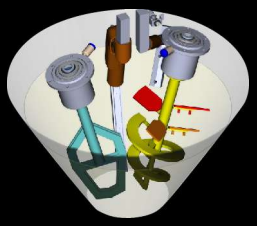

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Evolving with Technologies

The Lesner Bridge in Virginia Beach, Va., consists of twin precast concrete segmental box-grider bridges erected by span-by-span and balanced-cantilever methods. All Photos: RS&H.

RS&H partners with clients and contractors to improve concrete segmental bridge designs and construction engineering, to provide inspection oversight, and to help codify best practices and innovations.

by Craig A. Shutt

RS&H has made a name for itself with its history of design and construction management on concrete segmental bridges. These efforts continue to bring in new projects and help the company expand to new clients, geographies, and markets. As the firm continues its strong growth, it is also helping to improve design and construction concepts by codifying best practices and working on innovations to advance the industry.

"Our work on segmental bridges on the construction management side of our business has gotten our foot in the door with new clients and helped us expand," says Timothy Barry, vice president and bridge construction leader at the Jacksonville, Fla.–based firm. "Clients have noticed our work in that area, and our efforts to advance new ideas have caused owners to seek out our expertise."

The firm, established in 1941, has worked on concrete segmental bridge construction projects with the Florida Department of Transportation (FDOT) since the mid-1980s and has been engaged with the American Segmental Bridge Institute (ASBI) committees and task groups. "Our expertise and FDOT's experience have created a strong partnership that has advanced FDOT's approach to segmental bridges," explains Doug Geiger, senior vice president and construction management practice director. "FDOT has been a leader in these designs and has encouraged new techniques in the industry."

That encouragement gave RS&H the opportunity to advocate for new concepts and help codify them, adds David Sweeney, chief executive officer. "We evolved and learned best practices as we oversaw segmental bridge construction and saw the advantages they offered. Then we worked with FDOT to improve the details as issues arose. Now, that expertise is helping us expand to other states as we become known for our involvement in best-practice evolution through detail and specification development."

Diversity Drives Innovation

Sweeney believes that RS&H's ability to drive new solutions results from the diversity of its clients and partners. "Few professional-service companies actively work across the range of transportation sectors that serve land, air, and space," he says. "We design roads, bridges, airport terminals, runways, military and commercial launch sites, and a variety of [other] complex projects. Our experience with each of those creates solutions that can work in other areas."

One example is a concrete structure built for the National Aeronautics and Space Administration (NASA) launch facility in Wallops Island, Va. RS&H's bridge division worked with the aerospace division to design an enplaning ramp that carries the launch vehicle from the roadway grade to the elevated launch position. "Our bridge designers could apply their knowledge to this aerospace project and create a workable and site-appropriate solution," Sweeney explains. "That type of cross-sector application can bring considerable value to our clients and partners across all of the sectors we serve. We take everything we learn across the board and find ways to apply it to other sectors."

'Few professional-service companies actively work across the range of transportation sectors that serve land, air, and space.'

The firm also provides turnkey services from start to finish, notes Geiger. "Our skill set carries the project from inspection of the site and development of design concepts through construction management to the end of construction. Additionally, we provide in-service inspection for bridges, which is required on a two-year inspection cycle, as mandated by most bridge owners. Clients recognize that

we know every aspect of the project, and that adds value for them in any type of project."

RS&H has worked to stay at the forefront of new developments, and it has seen many changes and advancements. "The segmental bridge industry has been changing rapidly since the early 2000s, as it addresses issues and develops new specifications, new practices, and new technologies," says Barry. "We've had a front-row seat and contributed heavily to ASBI to provide input and ideas. New technologies are developing with almost every project, and plans evolve with those [innovations]."

An example is the Interstate 95/Interstate 295/State Road 9A North Interchange Project in Jacksonville, Fla., a precast concrete segmental balanced-cantilever overpass completed in 2010. "Segmental design and construction was instrumental because its longer spans addressed the difficulty in constructing this overpass over existing roadways and on a tight radius to limit right-of-way acquisition," Barry explains.

It was the first structure to require the use of duct couplers for joining post-tensioning ducts at segment joints. This technology was developed during the project and implemented immediately. It has now become a standard in the industry.

RS&H worked with the owner (FDOT), contractor (Superior Construction of Jacksonville, Fla.), and post-tensioning system supplier as the owner's representative during construction to refine the technology. "It contributed to our role as an industry leader and allowed us to continue growing our segmental experience, helping our clients and expanding our expertise," Barry says. (For more on this project, see the article in the Winter 2011 issue of *ASPIRE*®.)

Collaboration Is Key

Advancements are aided when stakeholders remain open to ideas and the construction team pools its knowledge and works collaboratively, says Sweeney. "Success depends a lot on how open the owner is to change. FDOT has been very progressive, which helps advance new concepts. When we can bring together the right stakeholders to share ideas and consider possibilities, we get the benefit of a lot of new perspectives."

RS&H's first design-build project as lead designer was the 19-span Veterans Memorial Bridge in Martin County, Fla., that crosses St. Lucie Waterway. The project features concrete beams and drop-in post-tensioned spliced girders.

Design-build delivery methods have aided collaboration, but only under the right circumstances. About 15% of the firm's design portfolio features design-build projects. "It's not always the best approach for us," he says. "The key factor is whether we are carrying the proper amount of risk for our level of participation in the project. The sweet spot on design-build for us comes on larger projects with higher construction values. They give us more opportunity to involve more of our resources to drive toward cost-effective solutions in partnership with our contractor teammates."

'Environmental and site access issues have become a driving force for using segmental concrete and for concrete in general.'

In regard to risk sharing, owners are adding requirements for contractors to accept more responsibility for quality control. "They want to minimize their level of risk factors and bring the contractor into this area more directly," Geiger notes. "As a result, our staff has evolved from doing hands-on testing and inspecting to doing higher-level engineering and providing an observational and advisory function for contractors and owners."

As a result, RS&H's construction engineering and inspection (CEI) management staff includes more engineers. About 45% of the inspection teams are composed of engineers, and 60% of the construction-inspection personnel have engineering degrees. "It has helped us differentiate ourselves because our inspections are done by engineers who understand the design concept and how the end product should perform," Geiger says. "That sets us apart from companies who perform mainly materials testing, as they are performing a different role than what we can provide."

An early design-build project for the firm was the Veterans Memorial Bridge in Martin County, Fla., completed in

The North Interchange Project in Jacksonville, Fla., features a precast concrete segmental box-girder overpass. The concrete segmental design resolved challenges in design and construction created by difficulties with placing the overpass over existing roadways and limited right-of-way. It was the first project to specify duct couplers for joining internal post-tensioning ducts, which is now a standard technique.

2013. Serving as the lead designer, RS&H, working with Archer Western Contractors (Walsh Group), designed the 3100-ft-long structure as a 19-span concrete-beam bridge using Florida I-beams and hammerhead-type piers and drop-in spliced girders. Two 250-ft spans allowed the bridge to cross the St. Lucie Waterway with fewer piers, helping to address the highly sensitive environmental concerns.

"This project was a great success for our design-build practice, which has become a large part of our firm's growth strategy," says Barry. "It reinforced our value and relationships with major contractors and expanded our transportation-client base beyond state and local agencies." The bridge won numerous awards, including a National Award of Excellence from the Design-Build Institute of America.

Environmental Concerns

Terrain issues often lead to creative concepts. On the 460 Connector project in Breaks, Va., RS&H performed CEI oversight of the twin 1733-ft-long cast-in-place concrete segmental box-girder structures erected by the balanced-cantilever method. The tallest bridges in Virginia, they were built from the top down because of the mountainous site.

'Success depends a lot on how open the owner is to change.'

"Cast-in-place segmental concrete superstructure construction made the most sense," says Barry. "Access from the ground was difficult, and large girders could not be delivered to the remote construction site. Environmental and site access issues have become a driving force for using segmental concrete and for concrete in general."

The 460 Connector also was significant for RS&H because it represented the firm's first CEI oversight project outside of its home state. "We were chosen, in part, because of the expertise we gained from our segmental experience in Florida," Barry says.

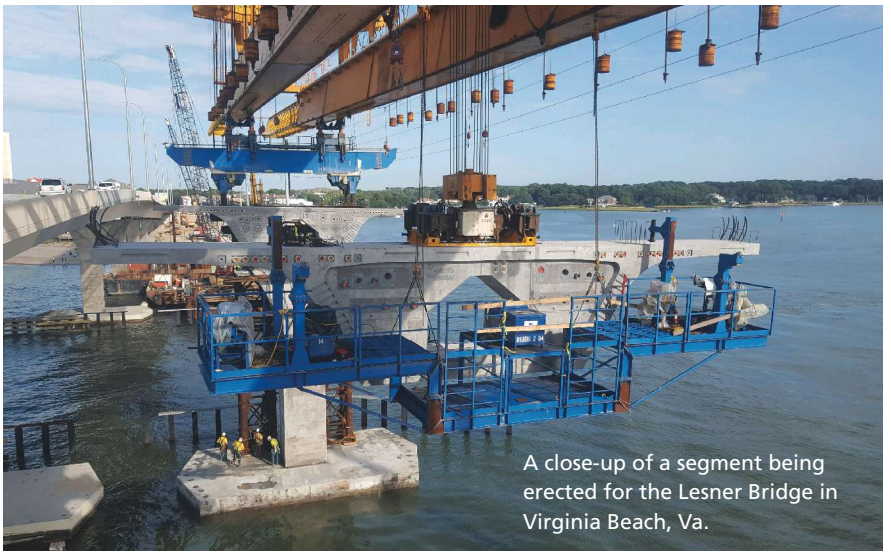
The firm's work went beyond construction oversight, however. "We also were tasked with developing new segmental specifications for the project and for VDOT [Virginia Department of Transportation] as a whole. The project was a significant growth opportunity for us as a firm and grew our segmental reputation as well."

Embracing Innovation

The 460 Connector project led to further expansion in Virginia, including CEI oversight for the Lesner Bridge replacement project. This ongoing project features twin 1575-ft-long precast concrete segmental box-girder bridges for a new client, the City of Virginia Beach. "A concrete segmental design was chosen due to difficult conditions on the site and for aesthetic reasons. This is a significant structure for the city, and both aesthetics and long-term durability were very important to them," Barry says. For RS&H, the project "was significant because it continued our segmental experience on a broader scale and added a new client outside of Florida."

A key element of the project's design was the goal of achieving a 100-year lifespan. The designer, FIGG Engineering Group, addressed that goal by specifying high-performance 8-ksi concrete. "It was an unusual product to specify as a production-level concrete," says Barry. Because of the highly aggressive environment adjacent to the Chesapeake Bay, the concrete had to achieve a low

The 460 Connector in Breaks, Va., features twin cast-in-place concrete segmental structures that are the tallest in the state. RS&H also assisted the Virginia Department of Transportation with the development of segmental bridge specifications for this and future projects.



A close-up of a segment being erected for the Lesner Bridge in Virginia Beach, Va.

permeability, requiring testing for every placement. The designer also specified corrosion-resistant reinforcing (CRR) steel. A requirement in Virginia, CRR steel adds to the long-term durability and less steel can be used because of the higher-grade steel used to satisfy the CRR requirements.

"As the owner's CEI consultant, RS&H understands its role with long-term durability by embracing these innovations and providing the level of oversight to ensure they are met," says Sweeney. "We understand that our clients rely on us to make sure they are getting what they paid for."

Innovations continue with every project, such as the Wekiva Parkway Section 6 project just getting underway in Orlando, Fla. Site conditions and environmental concerns made a cast-in-place segmental box-girder design the best choice, Barry says. The 2068-ft-long structure will be the first in the country to use new post-tensioning technology involving flexible filler instead of grout.

"It was significant for us to be chosen to provide construction oversight for this project, as it signifies our commitment to the industry and our service to our clients to help further the industry by embracing new technologies," Barry says. "It also expands our segmental and major concrete bridge resume, positioning us for further growth."

Geiger also looks forward to digging into this new concept. "The segmental industry continues to move forward with new technologies, and we're right there with them. We take pride in the fact that FDOT is showing great faith in us to oversee this new technology. It could be the future; we don't know yet. But it'll be exciting to see how it works."

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

RS&H's Evolving History

RS&H was founded in 1941 by engineers George B. Hills and John F. Reynolds and architect Ivan H. Smith. They decided to combine architectural and engineering capabilities to create a firm that would be more efficient than their separate small firms. With World War II imminent, they focused on military projects, including what would become NASA's Cape Canaveral facility in Florida.

After the war, the firm designed power plants, airports, and industrial facilities, adding offices throughout the Southeast. In the 1960s, it worked closely with NASA's manned spaceflight program and the U.S. Air Force's missile program. Over the next 20 years, it added several subsidiaries and affiliates, increasing staff and offices across the United States.

RS&H returned to an employee-ownership model in 1990. Today, the firm has 1089 employees in 50 offices focused in six markets: transportation, aviation, aerospace, corporate, defense, and health and science. It ranks 70th in *Engineering News Record*'s Top 500 Design Firms. It also ranks 11th in *Roads & Bridges'* Top Bridge Design Firms.

Rendering of Wekiva Parkway Section 6 project in Orlando, Fla., which will include new post-tensioning protection technology using flexible filler rather than grout. With construction beginning in late 2017, it is scheduled for completion in spring 2021.

Designing Precast, Prestressed Concrete Bridge Girders for Lateral Stability: An Owner's Perspective

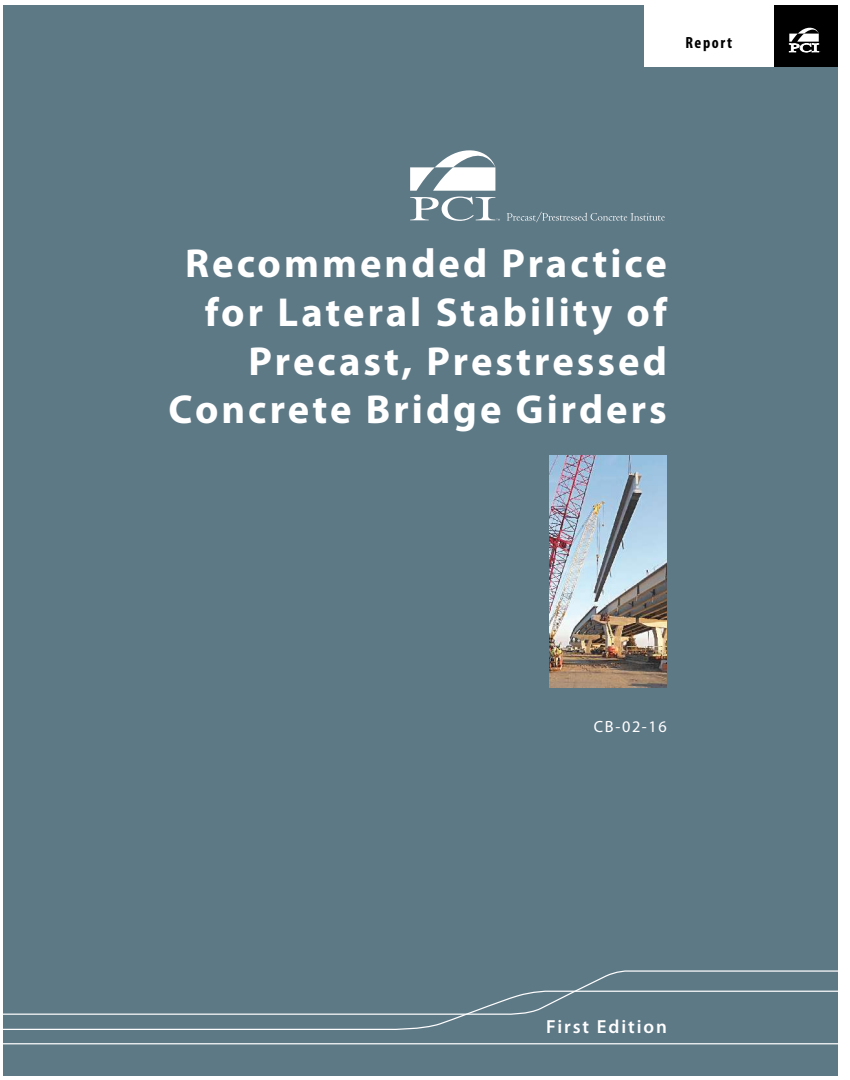
by Richard Brice, Washington State Department of Transportation

The Washington State Department of Transportation (WSDOT) investigates initial lifting, hauling, and erection conditions during the design of precast, prestressed concrete bridge girders. The design engineer's objective, stated simply, is to be reasonably satisfied that safe handling of girders can occur at all stages of construction.

The following excerpts from the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] show that constructability, safety, and stability must be considered by the design engineer.

> Article 1.3.1 Bridges shall be designed for specified limit states to achieve the objectives of constructability, safety, and serviceability, with due regard to issues of inspectability, economy, and aesthetics, as specified in Article 2.5.
>
> Article 2.5.1 The primary responsibility of the Engineer shall be providing for the safety of the public.
>
> Article 2.5.3 Constructability issues should include, but not be limited to, consideration of deflection, strength of steel and concrete, and stability during critical stages of construction. Bridges should be designed in such a manner that fabrication and erection can be performed without undue difficulty...
>
> Article 5.5.4.3 Buckling of precast members during handling, transportation, and erection shall be investigated.

The lateral stability of precast, prestressed concrete bridge girders is an important constructability and safety concern. Lateral bending failures are sudden, catastrophic, costly, and they pose a serious threat to surroundings and people, including the traveling public during transportation of girders from fabrication facilities to bridge sites. Investigation of potential instability conditions is well within the purview of the design engineer.



Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders contains state-of-the-art analysis techniques and best practices for lateral stability of precast, prestressed concrete bridge girders.

Lateral-Stability Design

WSDOT has designed precast, prestressed concrete girders for lifting and hauling for more than 25 years. When spans were generally less than 120 ft long, 120 ft long, bulb-tee and wide flange girder sections were not particularly deep, and stability was not a significant concern. Handling design consisted of evaluating stresses during lifting from the form and hauling to the bridge site.

High-performance/high-strength concrete (HPC/HSC) is now a standard material for the fabrication and construction of precast concrete girders. Among many other advantages, HPC/HSC offers higher concrete strength that allows girders to accommodate a greater precompression force from pretensioning. The increased precompression force, achieved by utilizing 0.6-in.- or 0.7-in.-diameter strand, translates to the design of significantly longer girder spans.

Some owners are extending the spans of typical AASHTO-type girders. These shallow Type II, III, and IV girders have relatively narrow flanges and may not have adequate lateral stiffness to resist lateral bending forces during handling. Other bridge owners have developed wide-flange girders to accommodate precompression forces commensurate with the strength of HPC/HSC and to provide greater lateral stiffness. These girders offer span lengths in excess of 200 ft.

Long-span girders fabricated with HPC/HSC present many challenges. Of primary concern are the lateral stability of long, slender girders and fabrication of these girders in existing stressing beds that were not designed for the larger pretensioning forces and girder sections. Working with local fabricators, WSDOT developed a new design methodology. The primary goal is to support optimized fabrication by determining the least required concrete strength at transfer and lifting, while achieving adequate stability of the girder during lifting and hauling operations. Brice, Khaleghi, and Seguirant[2] give a detailed description and example of this design procedure. The design outcomes include support locations during lifting and hauling, minimum concrete strengths at lifting and shipping, and, if necessary, temporary top-strand requirements.

Stability Design Parameters

The key stability design parameters are camber, sweep, dynamic loading effects, hauling vehicle characteristics, and maximum superelevation along the haul route. Other parameters can include lifting device rigidity and eccentricity, and bunking locations and eccentricity, depending on testing or experience. A common argument against consideration of lateral girder stability by the design engineer is that the contractor's means and methods, and thus many of the key parameters, are unknown at the time of design.

Successful past practices, contractual requirements, measurements, and conservative estimates are reasonable bases for setting the necessary parameters. Design engineers routinely estimate camber. Construction specifications typically provide tolerances for sweep, lifting device placement, and bunking locations. The maximum superelevation can be determined for likely project-specific haul routes or, more generally, the existing roadway infrastructure throughout a region. For other parameters, the design engineer can assume conservative values that increase predicted stresses and reduce factors of safety related to lateral stability.

Haul-truck characteristics are the most difficult parameter to establish. Fabricators in Washington state have been proactive regarding stability and have probable values of hauled weight per axle, overhangs, rotational stiffness per axle, and height of girder center of gravity above axle for typical girder transport vehicles. The WSDOT *Bridge Design Manual* incorporates these values as standard stability design parameters.[3] (A standard method for measuring rotational stiffness is not available. Mast,[4,5] and Seguirant[6] report placing girders on haul trucks and measuring rotations to determine stiffnesses.)

WSDOT recently collaborated with local fabricators and haulers to develop a new method for incorporating haul-truck rotational stiffness into lateral-stability design. Rather than using measured values for a specific hauler's equipment, engineers instead estimate the minimum rotational stiffness needed to satisfy hauling design requirements. This method results in a proposed hauling scheme that is compatible with a variety of hauling equipment.

Communicating Assumptions and Responsibilities

At the time of design, engineers do not know the means and methods for lifting and transport of girders. Reasonable estimates are the basis for stability design. WSDOT provides a proposed lifting and hauling scheme in contract documents and lists all relevant assumptions, including the estimated minimum haul truck rotational stiffness. When contract documents provide design assumptions, bidders can plan alternative lifting and shipping schemes and account for cost and schedule implications, leading to more accurate bids. Based on this experience, other owners are encouraged to work with local fabricators, haulers, erectors, and contractors to establish reasonable stability design parameters.

WSDOT provides design assumptions in contract documents by listing assumed stability parameters common to all projects, such as lifting device rigidity and eccentricity, girder lateral sweep, and dynamic loading factors, in the WSDOT *Standard Specifications for Road, Bridge and Municipal Construction*.[7] Project-

Maximum midspan vertical deflection at shipping	L	L_1	L_2	K_q Minimum shipping support rotational spring constant	W_{cc} Minimum shipping support center-to-center wheel spacing
$3^7/_8$ in.	5 ft 0 in.	10 ft 0 in.	10 ft 0 in.	50,000 k-in./rad	72 in.

Example of a girder schedule showing stability parameters. Figure: Washington Department of Transportation. Note: L = Distance from end of girder to lifting point; L_1 = Distance from one end of girder to support point during shipping; L_2 = Distance from other end of girder to support point during shipping.

specific parameters, such as lift and bunk locations, camber, and haul-truck rotational stiffness and wheel spacing, are shown in a girder schedule in the contract plans. The figure on the previous page shows an excerpt from WSDOT girder schedule.

The design engineer, when considering lifting and hauling stability concerns, does not bear full responsibility for safety throughout the duration of the construction project. Means and methods of girder handling, transport, and erection are well within the scope of work of the fabricator, hauler, erector, and contractor. Contract documents must clearly assign responsibilities to these parties. Section 6-02.3(25)L1 of the WSDOT *Standard Specifications for Road, Bridge and Municipal Construction* states that "the contractor is responsible for safely lifting, storing, shipping and erecting prestressed concrete girders." Recent amendments to these specifications provide parameters for performing lateral-stability analyses as well as clarification of requirements and responsibilities. The contractor and subcontractors, the fabricator, haulers, and erectors then assign responsibilities among themselves.

Consequences of Ignoring Stability During Design

Designs that do not consider girder stability are more likely to require postbid design modifications. These modifications are highly undesirable. They can lead to extensive redesign of girders, lengthy review cycles, delays in schedules, and significant changes to material quantities and geometric aspects of the bridge.

Design engineers are required to check girder stresses at transfer and to indicate the minimum concrete release strength on plans. If a lack of stability prevents the lifting of the girder from the casting bed, these computations become meaningless. Higher concrete strengths and restranding may be necessary. Other than the cross section, the revised girder may not bear any similarity to the original design.

Stability improves when handling support locations are moved in from girder ends. Temporary strands reduce tensile stresses at the support and harp-point locations. However, temporary strands affect long-term camber, and changes to camber affect the slab haunch buildup and bridge geometric elements such as bearing seat elevations. Significant changes in slab haunch concrete quantities can be the result for girders with wide top flanges. Additional prestressing force may be needed to accommodate an increased dead load.

WSDOT approach adopts the practice that the first line of defense against these types of postbid changes is the design engineer.

Implementing Stability Design

State-of-the art analysis techniques, best practices, and industry recommendations have been developed and published.[2,8] Girder stresses and stability at initial lifting and hauling are integral elements of the design process. Lifting and hauling conditions are often a governing design case. Designing for optimized fabrication and girder stability involves complex, iterative analytical procedures. Properly implemented tools are essential for lateral-stability design to be a common and routine practice.

WSDOT has successfully implemented the practice of lateral-stability design with sophisticated software tools. WSDOT's prestressed concrete girder design software—PGSuper™ for pretensioned girders, PGSplice™ for post-tensioned spliced girders, and PGStable™ for general precast concrete girder stability analysis—incorporates the necessary analytical procedures to enable engineers to arrive at acceptable design solutions quickly. These tools are part of the BridgeLink™ suite of bridge engineering software that provides the critical link between the state-of-the-art and everyday practice (see http://www.wsdot.wa.gov/eesc/bridge/software/index.cfm?fuseaction=software_detail&software_id=69).

Summary

As bridge owners make use of longer, more slender girders, stability becomes a serious concern. Engineers should become familiar with these concerns and address them during design. Stress and stability considerations during lifting and hauling should become a routine part of precast, prestressed concrete bridge girder design. Excellent design tools and resources are available (see references). Providing complete design assumptions in contract documents enables prospective bidders, fabricators, haulers, and erectors to address and account for possible changes to proposed lifting and hauling schemes during the bidding process.

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EDITOR'S NOTE

A Perspective article on this important topic written by a consulting engineer and a precast plant engineer, both of whom were instrumental in the writing of the* PCI Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders*, appeared in the Fall 2017 issue of* ASPIRE®*.

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PROJECT

Wynooski Road Bridge over the Highway 99 West Bypass

by Eric E. Bonn, OBEC Consulting Engineers

After 29 years in the making, the first phase of the Newberg-Dundee Bypass is almost complete. Currently, Oregon Route 99 West serves as both the main street for the cities of Newberg and Dundee, Ore., as well as a major transportation route between the Portland, Ore., metropolis and the Pacific Coast. Long backups and delays are common. This bypass facility, when complete, will be an 11-mile-long, four-lane, limited-access expressway on a fully new alignment south of both Newberg and Dundee. The first phase consists of 4 miles of 2-lane roadway and includes the grade-separated Wynooski Road Bridge over Highway 99, a significant arterial into the south end of Newberg.

The crossing location is pinched between a major industrial facility to the south and the 60-ft-deep Hess Creek drainage to the north. The existing Wynooski Road alignment also ran along the proposed bypass alignment for almost 300 yd. The resulting design moved the Wynooski Road Bridge to the top of the drainage slope, with a 603-ft-radius horizontal curve where the road goes over the bypass roadway. The bypass is in a cut section as it drops down to cross Hess Creek; therefore, a minor vertical curve was needed on the Wynooski Road Bridge to provide adequate vertical clearance underneath. The entering and exiting grades are 3.8% and -5.0%, respectively, and the resulting finish grade at the abutment is a minimum of 8 ft above the existing ground.

Post-tensioned concrete box girders and steel plate girders were considered for the Wynooski Road Bridge. The concrete structure was selected for multiple reasons:

- The cast-in-place (CIP) superstructure could be formed to follow the vertically and horizontally curved alignment, including the 4% superelevation.
- Prestressed concrete has a long and successful history in Oregon, exhibiting exceptional durability with minimal maintenance required.
- Concrete is also consistent with the other structures on the bypass, which all use precast, prestressed concrete girders.

Aerial view of bridge formwork showing horizontal curve of structure. Photo: Oregon Department of Transportation.

The bridge needed to cross over both the current phase of the bypass plus the future 4-lane build-out. Plus, the approaches to the crossing could not be supported on tall, wall-supported fills due to settlement and slope-stability concerns. Therefore, one end of the bridge was lengthened until it nearly met the existing ground at the west end. The resulting structure is 685 ft long and consists of four spans with lengths of 120, 210, 210, and 145 ft. The continuous box

The completed bridge with aesthetic treatment on the exterior face of the barrier rail. Photo: OBEC Consulting Engineers.

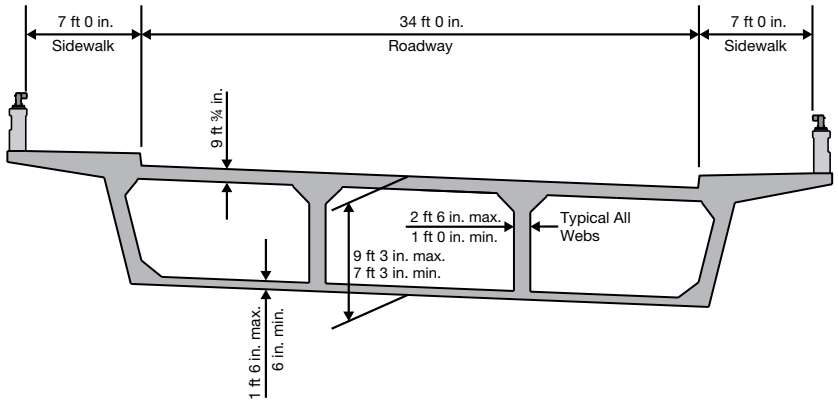
profile

WYNOOSKI ROAD BRIDGE OVER THE HIGHWAY 99 WEST BYPASS / NEWBERG, OREGON

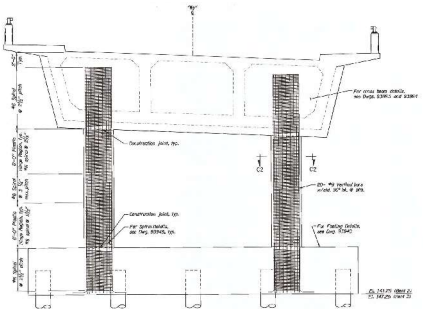
BRIDGE DESIGN ENGINEER: OBEC Consulting Engineers, Eugene, Ore.

PRIME CONTRACTOR: Wildish Construction Co., Eugene, Ore.

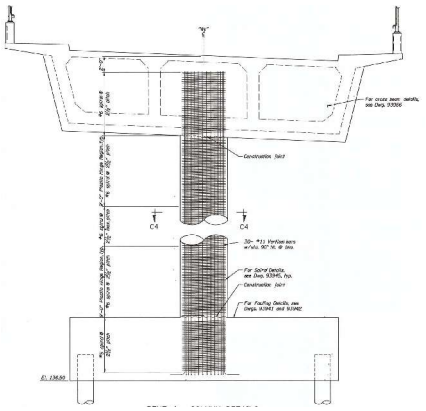
POST-TENSIONING CONTRACTOR: Schwager Davis Inc., San Jose, Calif.



Typical section of cast-in-place box girder. Figure: OBEC Consulting Engineers.



Bent 2 elevation. Figure: OBEC Consulting Engineers.



Bent 4 elevation. Figure: OBEC Consulting Engineers.

girder has a minimum depth of 7 ft 3 in., with 9-ft 3-in.-deep parabolic haunches at all interior bents. The span-to-depth ratio is approximately 29, resulting in a very slender appearance. The haunches extend for a distance of one-fifth of the span length on either side of the crossbeams to simplify the generally complicated forming geometry over most of the bridge's length. The depth of the haunches was minimized to provide the necessary vertical clearance beneath the bypass without raising the roadway alignment, which would have required additional bridge lengthening.

Wynooski Road Bridge's cross section includes a 34-ft roadway and two 7-ft-wide sidewalks. Including the rails, the total bridge width is approximately 50.4 ft. A three-cell box girder with a web spacing of 12 ft 6 in. was selected to coordinate with the column configurations, provide room for the necessary number of post-tensioning ducts, and limit the top slab overhangs to one-half of the web spacing per Oregon Department of Transportation (ODOT) requirements. The exterior webs are sloped 1:4 (horizontal to vertical). The raised sidewalks are integral to the box girder and act as the top flange in the overhangs. The thickness of the top slab above the cells is a constant 9.75 in. The webs and bottom slab have minimum thicknesses of 12 in. and 6 in., respectively, and thicken at the bents. The crossbeams of the interior bents are integral with the box girder.

Bents 2 and 3 each have two 4-ft-diameter columns. Bent 4 is located in the future median of the bypass and, with the alignments of Wynooski Road and the bypass intersecting at a 60-degree angle, a single 6-ft-diameter column was selected, thus allowing the crossbeam to remain perpendicular to the box.

The bridge is supported on driven steel-pipe piles. Concrete drilled shafts were considered, but they could not develop the necessary capacity in the site's soft, deep foundation soils. One of the geotechnical borings was advanced to a depth of 300 ft and encountered only clay soils. Therefore, large pile caps at the interior bents were needed to fit the required number of piles and space them as necessary to resist overturning forces. At bents 2 and 3, the pile caps are 22 ft by 44 ft and support both columns; the bent 4 pile cap is 34 ft square. During design, the 8-ft thickness of bent 4 caused concern that excessive heat of hydration might develop during the concrete curing. To address this issue, the bent was divided into two 4-ft-thick layers with a horizontal construction joint.

Two different concrete mixtures were used in the superstructure. The bottom slab and webs used 5-ksi concrete. The top slab and sidewalks used 5-ksi high-performance concrete (HPC) to increase wear resistance and reduce permeability. The HPC included 66% portland cement, 30% fly ash, and 4% silica fume for the cementitious material, as well as 5 lb/yd^3 of 1½-in.- to 2-in.-long polypropylene macrofibers. The water-cementitious materials ratio was limited to 0.40. All other bridge elements used 4-ksi concrete.

In addition to the HPC, other durability measures included limiting tensile service stresses in the box girder to one-half of the stress allowed by the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*, increasing the concrete cover over the top mat of top slab reinforcement to 2½ in., and eliminating all joints by using a continuous superstructure and semi-integral abutments. When using HPC in decks, ODOT does not require the use of epoxy-coated reinforcement in most regions of the state.

OREGON DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: 685-ft curved cast-in-place continuous post-tensioned 7 ft 3 in.- to 9 ft 3 in.-deep concrete box girder with spans of 120, 210, 210, and 145 ft and a deck width of approximately 50.4 ft. The bridge was built with integral piers and semi-integral abutments to eliminate all joints on the structure.

BRIDGE CONSTRUCTION COST: $5.3 million (approximately $155/ft^2)

Placing concrete for bent 2 footing. Note the scale of the large footing supporting both columns. Photo: OBEC Consulting Engineers.

The bridge was designed according to AASHTO LRFD specifications, AASHTO's *Guide Specifications for LRFD Seismic Bridge Design,* and ODOT's *Bridge Design and Drafting Manual.*

The total post-tensioning required was four hundred 0.6-in.-diameter strands tensioned to 75% of ultimate strength for a total force of 17,577 kip. Each web contained four ducts. The number of strands per web varied across the cross section in relation to the lengths of the individual webs as they spanned the curved alignment, with the maximum number of strands being 108 and 92 for webs on the outside and inside of the curve, respectively. Previous experience shows this also helps counteract some twisting of the box due to dead load torsion. The post-tensioning and grouting occurred without issue, except that a limited amount of concrete needed to be removed at one of the abutments to allow the expected shortening to take place without engaging the pile cap.

Placing concrete in the bottom slab of a box girder near a pier. Post-tensioning ducts can be seen in the webs. Photo: OBEC Consulting Engineers.

ODOT required a two-tiered approach to seismic design: the bridge is to behave elastically during a 500-year event and not collapse under a 1000-year event. The peak spectral accelerations at the site are 0.58*g* and 0.72*g* for the 500- and 1000-year events, respectively, where *g* is the acceleration of gravity. Most of the design was controlled by the 500-year event criteria. A Seismic Design Category (SDC) of D was determined for this site.

Because the bridge needed to get back down to grade, the column heights at bents 2 and 3 were much shorter than those at bent 4, which is located in the excavation for the bypass. The AASHTO guide specifications require individual bent stiffnesses to be relatively similar throughout the length of a bridge that is being designed for SDC D. Using two smaller-diameter columns at bents 2 and 3 provided most of the needed flexibility, with the remaining required flexibility achieved by placing the pile caps an additional 6 to 8 ft deeper to increase the column lengths.

Lengthening the columns had the additional benefit of reducing the overstrength plastic forces transmitted into the crossbeams and pile caps, which were required to be designed as capacity-protected members, meaning they are to behave elastically while the columns are allowed to develop plastic hinges during a seismic event.

One of the design challenges on this bridge was detailing the reinforcement in the crossbeams. The AASHTO guide specifications have prescriptive requirements regarding the quantity of reinforcement encasing the intersections of the columns and crossbeams, which can result in significant congestion and interference between the seismic, column, crossbeam, and box-girder reinforcement plus the post-tensioning ducts. Using a three-cell box allowed placement of the column reinforcement between the webs, and extending the ends of the crossbeams 1 ft past the outside face of the box minimized the

Placing concrete in web of the box girder. Photo: OBEC Consulting Engineers.

conflicts as much as possible. Inspection access hatches were provided in every cell at both ends of each span. Access holes were not placed through the crossbeams, to eliminate that additional design and detailing complication.

The Wynooski Road Bridge over the Highway 99 Bypass is a great example of how a post-tensioned CIP box girder can be applied to fit a geographically and foundationally challenging site with multiple restrictive design criteria, including horizontally and vertically curved alignments, high-seismic demands, and prescriptive detailing requirements. The flexibility of this structure type allowed for a cost-effective and attractive structure to advance the development of the long-awaited Newberg-Dundee Bypass.

Eric E. Bonn is a senior project engineer with OBEC Consulting Engineers in Salem, Ore.

Top slab formwork being constructed. Detailing the reinforcement to avoid interferences and congestion was challenging. Photo: OBEC Consulting Engineers.

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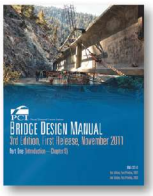


PCI Bridge Design Manual

3rd Edition, Second Release, August 2014

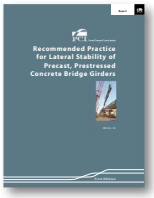
This up-to-date reference complies with the fifth edition of the *AASHTO LRFD Bridge Design Specifications* through the 2011 interim revisions and is a must-have for everyone who contributes to the transportation industry. This edition includes a new chapter on sustainability and a completely rewritten chapter on bearings that explains the new method B simplified approach. Eleven LRFD up-to-date examples illustrate the various new alternative code provisions, including prestress losses, shear design, and transformed sections.

www.pci.org/MNL-133-11

The PCI State-of-the-Art Report on Full-Depth Precast Concrete Bridge Deck Panels

The *PCI State-of-the-Art Report on Full-Depth Precast Concrete Bridge Deck Panels* (SOA-01-1911) is a report and guide for selecting, designing, detailing, and constructing precast concrete full-depth deck panels for bridge construction. This report is relevant for new bridge construction or bridge-deck replacement.

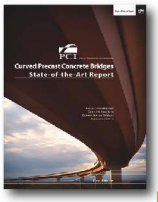
www.pci.org/SOA-01-1911



The PCI Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders

This is a new comprehensive methodology to analyze the lateral stability of long slender bridge girders. Technology has enabled the manufacture of increasingly longer girders. Slender girders present a lateral stability concern. Each stage of a girder's transition from the casting bed to its final location in the bridge is considered. These conditions include when handling from the top with embedded or attached devices and supported from below during storage, transit, or in various conditions on the bridge during construction.

www.pci.org/cb-02-16



The PCI State-of-the-Art Report on The Curved Precast Concrete Bridges

This report details the application of curved precast concrete bridge design, fabrication, construction techniques, and considerations through the study of twelve related projects and constitutes a state-of-the-art report on this topic. The document was written and intended to provide bridge owners, designers, fabricators, and engineers an up-to-date reference in developing precast concrete bridge solutions for curved geometric situations.

www.pci.org/CB-01-12

eBooks are fully searchable with hot links to references, enabling direct access to the internet.

Completed Trunk Highway 101 Bridge.
All Photos: Minnesota Department of Transportation.

TRUNK HIGHWAY 101 BRIDGE

by Paul Gronvall and Benjamin Jilk, Minnesota Department of Transportation

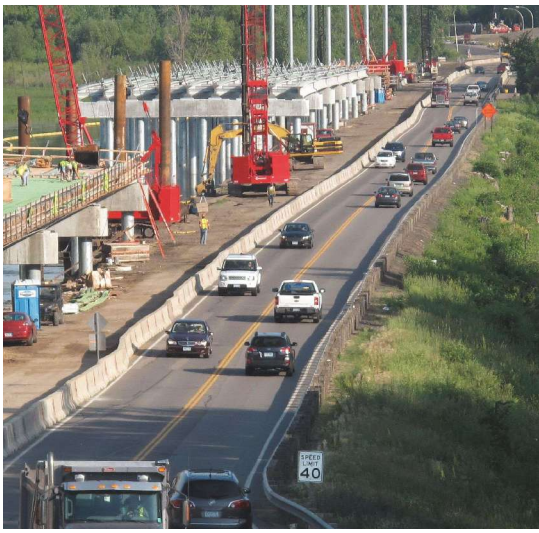
At the ground-breaking ceremony inaugurating the construction of the new Trunk Highway 101 Bridge reconnecting the cities of Chanhassen and Shakopee in Minnesota in June 2014, flood waters rose above the existing elevated roadway. As the rising waters slowly approached the ceremonial mound of soil that had been put in place to signify the breaking of ground on the project, they demonstrated why the project was needed. A flood-mitigation study was performed in 2011 to investigate ways to improve local and regional mobility during seasonal flooding events of the Minnesota River, which would force closures of the highway.

This crossing and the neighboring Trunk Highway 41 crossing in Chaska, Minn., had closed several times in the recent past, with closure times ranging from several days to several weeks and a projected cost to travelers of $1.675 million per day in 2030. The final design concept needed to minimize the risk of flooding without causing an increase in the 100-year floodplain elevation. A 4225-ft-long bridge across the Minnesota River floodplain was determined to be the preferred concept for mitigating flood risks by raising the bridge above the 100-year flood elevation and removing the existing causeway. The new bridge would provide four 12-ft-wide lanes for traffic, 8-ft-wide shoulders, and a 10-ft-wide multiuse trail separated from traffic to connect regional trails.

With a bridge being selected as the preferred concept to address flooding risks, an optimal bridge type that met all of the project requirements had to be determined. To arrive upon an optimal solution to span the floodplain, various combinations of substructure and superstructure types along with span configurations were considered as the final horizontal alignment and vertical profile were also being determined. Most of the water runs off the ends of the bridge into ponds where it is treated. Scuppers were provided at select locations to prevent ponding.

Pier Concept and Design

Selecting a pier concept to span the wide Minnesota River floodplain that minimized cost, schedule, and environmental impacts was of first importance. Open pile-bent piers are commonly used in Minnesota for bridges over streams and wetlands because they are cost-effective and relatively easy to build. Unlike typical concrete piers, open pile-bent piers do not require any temporary works be placed in the water to construct the



The existing causeway along with the temporary trestles served as a working platform during construction. Note the difference in the new and old roadway elevations.

profile

TRUNK HIGHWAY 101 BRIDGE / CHANHASSEN AND SHAKOPEE, MINNESOTA

BRIDGE DESIGN ENGINEER: Minnesota Department of Transportation, Oakdale, Minn.

PRIME CONTRACTOR: Ames Construction, Burnsville, Minn.

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

OTHER CONSULTANTS: Geotechnical engineer: Dan Brown and Associates, Sequatchie, Tenn.; Roadway engineer: Short Elliott Hendrickson Inc., St. Paul, Minn.

footing or any formwork to construct the columns. The piles within an open pile-bent pier function as both the foundation and as a permanent form to place the concrete infill while still being structurally utilized in the design. This type of pier lends itself to this application and was selected as the preferred concept for the Trunk Highway 101 Bridge.

Typically, the Minnesota Department of Transportation (MnDOT) limits the use of open pile-bents to sites where the height from top of pier to streambed is a maximum of 20 ft. For this project, the piers were significantly beyond this limit, with the tallest pier reaching a height of approximately 32 ft. Although these heights reached beyond the typical limit for open pile-bent piers, use of this type of pier was still the preferred concept. Therefore, further investigation was carried out to determine whether open pile-bent piers could meet structural demands and provide a safe route across the floodplain.

Based on the hydraulic report for the site, water flow rates during a flood event are minimal, if not static, and ice floes are not expected. Due to the low hydraulic demand on the site, an encasement wall around piles was deemed unnecessary and ice impact did not have to be included in the design.

Unique design criteria were developed to address the long-term durability and serviceability of the structure and its components while minimizing future maintenance needs. Serviceability—specifically, lateral deflection—was the governing factor in the design of the piers. There is a natural tendency of long bridges with relatively tall, flexible piers to "walk" or "migrate" in the direction of the longitudinal axis of the bridge under cyclic lateral loads such as braking and thermal forces. Criteria for limiting the lateral deflection of the piers

The bridge was constructed in multiple segments. The spiral welds are visible on the steel pipe piles that were filled with concrete after driving.

were set to address this phenomena by reducing these longitudinal movements through the stiffening of the open pile-bent piers. Also, this stiffening of the piers aids in protecting the expansion joint glands from tearout and deterioration, and limits undesired expansion bearing movements. All of these measures should reduce future maintenance needs and costs.

Initially, multiple rows of smaller-diameter battered piles were considered to increase the stiffness of the piers. With 40 piers on the project, this approach would have resulted in a significant increase in the amount of piling required and presented challenges in maintaining reasonable construction tolerances at the heads of the piles, considering their heights above the ground.

Instead, a single line of larger-diameter piles was selected for the design. Although the individual piles were more expensive on a per-foot basis, the overall project cost was reduced because fewer piles were used and the simplicity of driving piles plumb also saved money. During final design, two concrete-filled composite steel pipe pile sections were chosen. To ensure and maintain a clean inside wall on the steel pipe pile, the pile bases were driven closed-ended and filled with concrete later. For the shorter piers at both ends of the bridge, a 16-in.-diameter steel pipe pile was used, and, for the taller piers, a 30-in.-diameter steel pipe pile was used. The 30-in.-diameter composite steel pipe pile section was the first of its size and the largest composite pipe pile section used on any open pile-bent pier in Minnesota.

The final design of the pile-bent piers included an analysis that considered both combined axial and lateral load effects along with nonlinear soil-structure interaction. This analysis was used to determine the fixity point of the pile below the surface of the soil and the associated effective length for buckling capacity computations of the piles. Because the design was governed by serviceability criteria (specifically, lateral deflection), it was paramount that the design and properties of the piles maximize the available composite action between the steel pipe pile

CARVER COUNTY, MINNESOTA, OWNER

BRIDGE DESCRIPTION: A 4225-ft-long, 41-span, precast, prestressed concrete I-girder superstructure with a deck area of 333,456 ft^2 on open pile-bent piers

STRUCTURAL COMPONENTS: Three-hundred sixty-nine 45-in.-deep precast, prestressed concrete I-girders; open pile-bent piers composed of 408 concrete-filled steel pipe piles (30-in. and 16-in. diameters) with cast-in-place concrete pier caps; abutments supported by fifty-one 12-in.-diameter concrete-filled steel pipe piles; and a 9-in.-thick monolithic concrete deck

BRIDGE CONSTRUCTION COST: $24.4 million bid cost (approximately $73/$ft^2$)

Various techniques were used to construct the 13 deck segments in order to evaluate their effects on deck performance. Gang vibrators, as shown here, were used for one segment.

section and the 5-ksi concrete infill. Composite action is primarily achieved through two mechanisms: frictional bond transfer between the steel pipe pile section and the concrete infill and, for larger 30-in.-diameter spiral-welded pipe piles, the projection of the weld.

Because the upper portion of the piles is exposed to air and water, the piles were galvanized from the top of the pile to a minimum of 15 ft below the ground surface, to provide a level of protection against corrosion. Conventionally reinforced cast-in-place concrete pier caps were chosen for their simplicity and cost-effectiveness.

Precast, Prestressed Concrete I-Girder Superstructure

During the preliminary design phase, the preferred type of superstructure selected was precast, prestressed concrete I-girders. This girder type is a go-to solution in Minnesota for a low-cost and low-maintenance superstructure. Multiple suppliers in the area, quick turn-around time, and ease of construction make them the preferred option in most cases. For these reasons, precast concrete girders were the right solution for the Trunk Highway 101 Bridge.

HAMILTON FORM CREATES FUNCTION

21 CASE STUDY

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Dennis Fink, General Manager, Plant Operations Northeast Prestressed Products, LLC

The Project:
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The Challenge:
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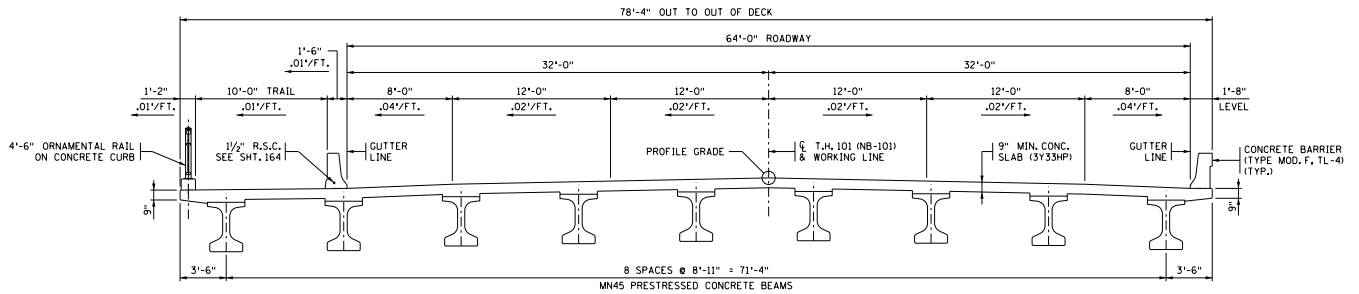
To span between the piers, 45-in.-deep MnDOT girders were selected. The typical bridge cross section consists of nine girders spaced at 8 ft 11 in., with the last three spans varying slightly because of a curve at the end of the bridge. The spans range from about 87 ft to about 105 ft in length. There are a total of 41 spans in 13 units separated by strip-seal joints. A unit consisted of

Typical cross section of bridge.



three or four spans. The girders were designed as simply supported, but additional reinforcement was provided over the piers in the bridge deck where there was no joint.

Deck Used to Compare Performance of Parameters

The bridge deck is 0.8 mile long, and it therefore provided a great opportunity to incorporate different experimental items to compare concrete placement methods and performance of the concrete deck. With the bridge deck separated into 13 units, each joint formed a physical separation in methods for deck placement. The standard method for placing decks in Minnesota was used as the basis of the comparison, and all the other deck sections had more stringent specifications aimed at improving deck performance, durability, and quality.

The variations included the wet cure time, the number and type of vibrators required for placement, reinforcing bar chair spacing, the inclusion of fibers in the concrete, and the maximum aggregate size in the concrete. Every permutation tried outside of the standard method proved to help reduce cracking. Epoxy-coated reinforcement was used in all concrete elements of the structure that were not completely under soil to increase durability and improve performance.

The bridge is composed of 41 spans and 40 piers. The deck area is 333,456 ft^2 and is supported by 369 precast concrete I-girders utilizing 738 bearing assemblies. The total cumulative length of concrete girders on the bridge is approximately 7.2 miles. Overall, 459 piles (408 in the open pile-bent piers and 51 supporting the abutments) were used to construct the bridge—that is the equivalent of more than 10.4 miles of piles. More than 81.5 million pounds of concrete and 2.4 million pounds of epoxy-coated reinforcement were used on the bridge. The 4225-ft length makes it the longest bridge in Minnesota using only open pile-bent piers for support.

The new bridge, completed in November 2015, provides a cost-effective solution to improve local and regional mobility during seasonal flooding events of the Minnesota River, which had formerly disrupted traffic in the region.

Paul Gronvall is a senior engineer and Benjamin Jilk is a principal engineer at the Minnesota Department of Transportation in Oakdale, Minn.

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PROJECT

INTERSTATE 91 BRATTLEBORO BRIDGE— A GATEWAY TO NATURE IN CONCRETE

by Garrett Hoffman, FIGG

Construction of the Interstate 91 (I-91) Brattleboro Bridge Project in Brattleboro, Vt., replaced twin existing bridges over the West River with a new long-span landmark bridge. The best value-selected, design-build project was designed by the team for the Vermont Agency of Transportation (VTrans). The new gateway bridge features a 1036-ft-long arching concrete bridge soaring 90 ft above the West River and built using balanced-cantilever construction. Two piers flank the river banks to support the three-span (263-515-258 ft) bridge.

Vermont's Bridge to Nature

It was important to VTrans and the surrounding communities that the new bridge serve as an icon and a gateway to Vermont. The bridge construction also needed to have minimal impact on the traveling public using the bridge, as well as those traveling under the bridge: vehicles on Vermont Route 30 (VT 30) (a major route for ski resorts), kayakers on the beautiful West River, and hikers on the West River Trail.

The design-build team was excited about the challenge of designing and constructing a beautiful, signature structure that represents Vermont. Overlooking the West River and mountainous valley, this bridge features viewing platforms for pedestrians, hikers, and visitors. True to its theme, "A Bridge to Nature," every detail of the uniquely shaped superstructure, including its piers, viewing platforms, and railings, complements Vermont's natural landscape. The piers feature Vermont-inspired stone-formed and stained concrete that blends with the local environment. A visual quality advisory team consisting of representatives from VTrans, the local aesthetic committee, and the bridge designer selected eco-friendly concrete stain colors, platform railing designs, and other aesthetic details.

The focal points of the bridge are the quad-wall piers, which emerge from the ground in sweeping organic forms and support the arching concrete spans. Each quad-wall pier is comprised of four concrete columns that individually curve outward in two directions, creating a symmetrical pattern. The three-dimensional (3-D) design and detailing of the columns resulted in a varying cross section and complex reinforcing steel configurations.

The designer, contractor, reinforcing steel fabricator, and formwork provider held workshops to ensure that all details were considered and to provide the most efficient design. The quad-wall system of the piers provides stability, and allowed the bridge superstructure to be built from above using balanced-cantilever segmental construction without temporary falsework in the river. This scheme minimized the impact of the project on the West River and West River Trail.

Every detail of the uniquely shaped superstructure complements the natural Vermont landscape. Each quad-wall pier is comprised of four concrete columns that curve outward in two directions, symbolizing stone trees emerging from the ground and supporting the arching concrete spans. All Photos: FIGG.

profile

INTERSTATE 91 BRATTLEBORO BRIDGE / BRATTLEBORO, VERMONT

BRIDGE DESIGN ENGINEER: FIGG Bridge Engineers Inc., Exton, Pa.

ROADWAY/GENERAL CIVIL ENGINEER: Sebago Technics Inc., South Portland, Maine

PRIME CONTRACTOR: PCL Civil Constructors Inc., Raleigh, N.C.

POST-TENSIONING CONTRACTOR: DSI, Freedom, Pa.

The new gateway bridge in Brattleboro, Vt., carries Interstate 91 over the West River, Vermont Route 30, and the West River Trail. Located in southern Vermont, the bridge provides a visual "gateway" to the state's mountains, valleys, and rivers.

Using self-advancing formwork (form travelers), 16-ft-long segments of the bridge were cast-in-place, alternating from one side of the pier to the other, until each cantilever arm reached 252 ft. When the cantilever arms on adjacent piers were complete, a small closure segment was cast to connect the two cantilever arms and form the span. Surveying and geometry control were a full-time endeavor to ensure that the two cantilevers would meet at a precise, midair target. Prior to casting the closure segment, the two cantilevers were longitudinally jacked apart to mitigate long-term creep and shrinkage effects on the relatively stiff quad-wall pier system.

Segmental Superstructure

To support the 104-ft-wide bridge deck carrying two lanes of traffic in each direction, a two-cell, three-web trapezoidal box girder was used. The use of a single bridge instead of twin bridges eliminated a major traffic shift and crossover section and improved mobility during construction. A variable-depth profile was used for structural efficiency and provided a natural aesthetic as the bridge spans the valley. With a depth of 12 ft 7 in. at midspan and 30 ft 7 in. at the piers, the segments were large relative to the human scale. The biggest segments contain 221 yd^3 of concrete and took 6 hours to cast. Another unique feature of the box-girder section is the vaulted-bottom soffit that runs the full length of the underside of the bridge. This 20-ft-wide, 4-ft-deep, barrel-like shape adds dimension to the soffit, which would otherwise have a flat 55-ft-wide surface.

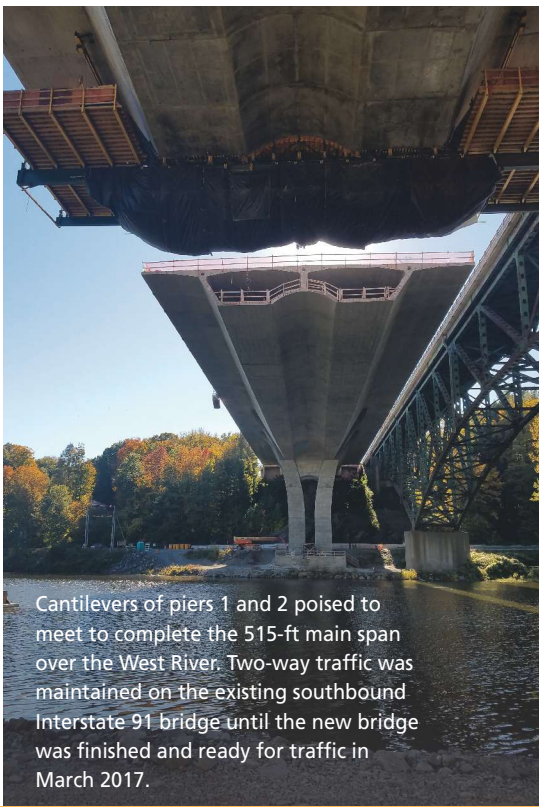
Continuous mild reinforcement through segment joints and a grouted post-tensioning system create continuity of the cast-in-place segments. Top slab tendons were used during cantilever construction, while bottom slab and external draped tendons provided continuity after span closures were cast. Transverse top slab tendons balanced the deck design. All tendons have multiple layers of corrosion protection, including a 2¼-in.-thick integral wearing surface, increased concrete cover, low-permeability concrete, plastic ducts, and grout.

User Experience

Travelers along VT 30 experience this distinctive bridge from a side vantage point before they then travel under the bridge. They see the vaulted soffit stained with a blue color to mimic the sky. The arching, long span of the superstructure is half as deep as the former bridge and opens up the view of the landscape. To match the surrounding environment, a permanent concrete earth-toned stain was applied to all sides of the bridge superstructure. The piers were cast with a texture that simulates Vermont stone, which creates a dramatic look with different natural colors along the 60-ft-tall piers. The upper "fins" of the piers cradle the superstructure and were hand-sculpted using shotcrete to match the stone texture below.

Community Involvement

The design-build team led monthly "trail talks" to give the community the opportunity to walk up the West River



Cantilevers of piers 1 and 2 poised to meet to complete the 515-ft main span over the West River. Two-way traffic was maintained on the existing southbound Interstate 91 bridge until the new bridge was finished and ready for traffic in March 2017.

VERMONT AGENCY OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: The new bridge is a 1036-ft-long three-span segmental cast-in-place concrete box girder bridge built utilizing balanced-cantilever methods with form travelers.

STRUCTURAL COMPONENTS: A single dual-cell segmental concrete box girder with transverse and longitudinal post-tensioning with an overall deck width of 105 ft.

Trail to the bridge with the team and learn about the design and construction of the monumental bridge.

The bridge designer also created 3-D-printed models of the bridge in snap-together pieces to make hands-on learning tools for student education programs at Brattleboro-area schools. During both design and construction, the design-build team visited several local schools to discuss the construction and engineering behind bridge building. Custom FIGG Bridge Boxes, which contain education tools to inspire and teach children about science and engineering, were part of the project activities.

On Saturday, March 4, 2017, more than 800 local residents and visitors took advantage of an opportunity to walk across the new bridge before it opened to traffic. Representatives from VTrans and the design-build team were on hand to answer questions as the public journeyed across the bridge. The bridge was dedicated on September 12, 2017.

Durability

VTrans required a 100-year design life, but the bridge designers focused on providing a 150-year design life. Concrete segmental bridges as a structure type are inherently durable due to sustainable materials and the use of biaxially post-tensioned concrete. Concrete mixture proportions were designed for low permeability and the addition of calcium nitrite enhanced resistance to chloride penetration. Also, stainless-steel reinforcing bars were used in the bridge deck to enhance the deck life. Incorporation of durability into the initial design will ensure the least possible maintenance and cost over the life of the bridge.

Conclusion

The design-build team provided creative solutions to the bridge challenges, including the use of balanced-cantilever construction, which eliminated the need for temporary falsework in the West River. Compared with its predecessor, the single bridge provides a smaller overall footprint. With fewer footings and abutments, it required less erosion control and had fewer areas of environmental impact during construction than the original bridge concept during the request-for-proposal phase. The single concrete bridge also provides ease of inspection inside the bridge, requiring less mobilization during future annual inspections. A best-value concrete segmental solution provided a one-of-a-kind gateway to nature in the beautiful state of Vermont.

Construction of Pier Table 1. Pier 1 soared 70 ft in the air while vehicular traffic was maintained on Route 30 and river remained open for recreational boating.

Pedestrians enjoy the West River Trail and provide scale to the grand 60-ft-tall quad-wall piers of the bridge. The piers have a textured concrete surface inspired by the area's native stone. The barrel shape cast into the soffit is colored blue to match the sky.

Garrett Hoffman is the northeast regional director for FIGG in Exton, Pa.

Balanced-cantilever construction allowed work to continue through the harsh Vermont winters. No temporary falsework was needed, which kept crews out of the water and allowed construction to continue on both sides of the river.

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PROJECT

Southbound Interstate 95 to Eastbound State Road 202 (J. Turner Butler Boulevard) Flyover Bridge

by Andrew Mish, Summit Engineering Group (a Modjeski and Masters company)

The intersection of Interstate 95 (I-95) and State Road 202 (SR 202) is a major traffic interchange south of downtown Jacksonville, Fla. I-95 carries north/south traffic through the heart of Jacksonville, while SR 202, also known as J. Turner Butler Boulevard, carries east/west traffic to beaches on the Atlantic Coast. Commuter traffic on both roads through the greater Jacksonville area is significant, totaling more than 200,000 vehicles per day. A major congestion and safety concern of the old interchange was that the southbound I-95 to eastbound SR 202 traffic exited to a stoplight. During rush hour, vehicles on this exit would consistently back up onto the interstate for a mile or more.

In 2014, the Florida Department of Transportation (FDOT) awarded a design-build contract for the redesign and construction of the I-95 and SR 202 interchange. Four design-build teams were selected for the short-list group to present proposals to the department. The proposals were evaluated using a combination of technical score and total price. (For FDOT's process of selecting design-build teams, see "Refining the Adjusted-Score Design-Build Process" in the Summer 2018 issue of *ASPIRE*®.) The winning team presented a redesigned interchange that consists of four bridge structures, new ramp configurations, new highway alignments, and the widening of the I-95 and SR 202 roadways. The signature bridge of the project is a curved, post-tensioned, precast concrete U-girder flyover bridge that carries southbound I-95 to eastbound SR 202, eliminating the traffic

Aerial view of the J. Turner Butler Flyover Bridge prior to casting the bridge deck. Photo: Modjeski and Masters.

profile

SOUTHBOUND INTERSTATE 95 TO EASTBOUND STATE ROAD 202 (J. TURNER BUTLER BOULEVARD) FLYOVER BRIDGE / JACKSONVILLE, FLORIDA

BRIDGE DESIGN, CONSTRUCTION, AND ERECTION ENGINEER: Summit Engineering Group (a Modjeski & Masters Company), Littleton, Colo.

PRIME CONTRACTOR: SEMA Construction, Orlando, Fla.

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

POST-TENSIONING CONTRACTOR: Freyssinet Inc., Sterling, Va.

backup problem. The bridge was opened to traffic on September 7, 2017.

The new southbound I-95 to eastbound J. Turner Butler Boulevard Flyover Bridge is a seven-span, 1342-ft-long structure. There are two superstructure units, with expansion joints at end bents and at pier 5. Unit 1 has four spans with a total length of 767 ft. Unit 2 has three spans with a total length of 575 ft. Span lengths vary from 140 ft to 232 ft. The overall width of the superstructure is 47 ft 6 in., which accommodates two 12-ft-wide travel lanes plus 8-ft and 12-ft shoulders. The structure is curved on a 1100-ft horizontal radius combined with a vertical curve that has an incoming vertical grade of +5.0% and an outgoing grade of -3.5%. The deck has a constant superelevation of 7.5%.

The superstructure is composed of curved, spliced precast concrete U-girders that are post-tensioned to form continuous spans. There are two 84-in.-deep constant-depth girder lines spaced at 23 ft 9 in. that support a 9-in.-thick deck, which includes a ½-in. sacrificial depth for grinding and wear. To minimize form changes, both the left and right girders are designed to be cast with the same 1100-ft radius. This casting method does not significantly affect the design, but it allows for vastly increased efficiency in girder production. The substructure consists of single-column piers supported on prestressed concrete pile foundations. Of the six interior piers, four use precast concrete pier caps that allow construction to take place with minimal falsework to accommodate the site conditions (see "Precast Concrete Pier Caps Aid Construction of Jacksonville Flyover Bridge with Tight Site Conditions." in this issue of *ASPIRE* on page 34). There was no room for formwork shoring that would be required for cast-in-place (CIP) concrete pier caps because any shoring would have interfered with traffic. A solution was needed that allowed casting and erection of the pier caps without any temporary shoring. The precast concrete caps were cast on site and erected onto temporary support brackets attached directly to the columns. They were designed to be cast flat for ease of construction, and erected to match the 7.5% cross slope of the bridge. Matching the cross slope with the cap provides a continuous and symmetrical aesthetic from the superstructure to the substructure.

Rationale for Integral Caps

There were three primary reasons for using integral caps on this project.

- They minimized the total structure depth from bottom of cap to top of deck by making the design more efficient with composite action between the CIP concrete diaphragm and the precast concrete cap. This was important to maintain traffic clearance both during construction and in the final alignment.
- They eliminate bearings, which require a large joint/gap between the bottom of the girder/diaphragm and the top of the cap. This eliminates the cost and long-term maintenance requirements for bearings.
- From an aesthetic perspective, they provide a seamless transition from the superstructure to the substructure, giving the appearance that everything was cast together.

Site and Construction Challenges

The flyover bridge is constructed over three major traffic crossings: southbound I-95, northbound I-95, and westbound SR 202. During construction, FDOT required that all lanes remain open to traffic. Only overnight lane closures were allowed, providing 6- to 8-hour windows for the

Curved precast concrete U-girder span over Interstate 95 during U-girder construction. The girders are supported with integral cast-in-place concrete diaphragms made composite with precast concrete pier caps. Photo: Seidler Productions.

construction and erection procedures that needed to occur in traffic areas. To facilitate construction, the maintenance-of-traffic plan was integral to the success of the project. Several traffic shifts were executed to open different areas of the project site for construction while maintaining all travel lanes, as required by FDOT.

To accommodate the constant flow of traffic through the jobsite, several innovative features were incorporated into the bridge design. Precast concrete pier caps were used at the interior piers. Pier locations were adjacent to traffic during construction, so using temporary shoring to support formwork was not an option. The precast concrete pier caps also served to support pier girders during construction, eliminating falsework towers within the traffic zone. Pier girders were erected on a temporary falsework tower at one end and on the precast concrete pier cap at the other end, with a large cantilever beyond the pier cap.

The cantilevered pier girders supported drop-in girders on strongbacks, which eliminated the need for falsework towers at the splice locations. Strongbacks were connected to girders

FLORIDA DEPARTMENT OF TRANSPORTATION, OWNER

OTHER MATERIAL SUPPLIERS: Bearing supplier: R.J. Watson Inc., Alden, N.Y.; Expansion joint supplier: D.S. Brown Company, North Baltimore, Ohio; Lightweight aggregate supplier: Carolina Stalite Co., Gold Hill, N.C.; Stainless-steel reinforcement supplier: SteelCON Supply Company, Jacksonville, Fla.

BRIDGE DESCRIPTION: A 1342-ft-long curved, spliced precast concrete post-tensioned U-girder bridge on an 1110-ft horizontal radius

STRUCTURAL COMPONENTS: 2675 linear ft of 84-in.-deep curved spliced post-tensioned precast concrete U-girders; four precast post-tensioned concrete pier caps 36-ft-long by 7-ft 6-in.-wide by 4-ft 6-in.-deep; two cast-in-place post-tensioned concrete pier caps 35-ft 8-in.-long by 8-ft 0-in.-wide by 9-ft 4-in.-deep; six single-column piers 4 ft by 7 ft; 11,220 linear ft of 24-in.-square precast concrete piles

BRIDGE CONSTRUCTION COST: $66.7 million (for construction of entire interchange, including three additional pretensioned bulb-tee girder bridges)

Pier girder supported by precast concrete cap and falsework tower during construction. Photo: Modjeski and Masters.

through a partial-depth diaphragm, supporting them from the top. This approach provided the minimum vertical clearance over traffic because no hardware projected below the bottom surface of the girders.

Span 6 of the Flyover 1 bridge is one of the longest spans in the structure, measuring 228 ft 11 in. Girder shipping weights limited the maximum piece length to 100 ft for pier girders and 115 ft for drop-in girders. Because of the pier locations and site geometry, a single drop-in girder could not span between pier girders. The solution was a temporary straddle bent to support two drop-in girders at the central splice location in the span. The straddle bent spanned approximately 70 ft to provide clearance for three traffic lanes, the barrier rail, and a clear zone behind the barrier.

Structure Design

The foundations are composed of 24-in.-square prestressed concrete piles driven to an average depth of 100 ft below grade. Test piles were driven and monitored at each bent location to ensure that the required load-carrying capacities were achieved. A single CIP column supports each interior pier. The column geometry was controlled by the amount of space in the median between northbound and southbound I-95 at pier 3, leading to a 4 ft by 7 ft rectangular cross section with $1\frac{5}{8}$-in.-deep vertical reveals.

A temporary straddle bent supports girders at the splice location near midspan over J. Turner Butler Boulevard during construction. Bridge deck overhang falsework brackets are attached to the girders after the integral cast-in-place concrete diaphragms have been cast to support work platforms and wet deck concrete during construction. Photo: Modjeski and Masters.

Interior piers use both CIP and precast concrete pier caps. CIP pier caps are located at interior piers 4 and 5. These piers were designed with slide bearings to accommodate girder movement due to post-tensioning, creep, shrinkage, and temperature fluctuations. All other piers were designed with precast concrete caps and integral diaphragms, relying on column flexibility to accommodate longitudinal movement. All pier caps were designed using staged post-tensioning to provide sufficient strength and serviceability during the multiple phases of construction and in-service loadings.

The superstructure of the flyover bridge is composed of spliced, precast concrete post-tensioned U-girders. It is the second structure using these curved girders in Florida, and it is the first project using these girders for FDOT. The structure is designed using time-dependent load-history analysis. Each stage of construction is included in the analysis, and the structure is aged 30 years to account for long-term creep and shrinkage effects.

The girders were designed for the entire life cycle, from casting in the precast concrete plant to final service and ultimate conditions in the superstructure. When initially stripped from the formwork and stored at the precast concrete yard, the girders were mildly reinforced. Handling devices were located at approximately 0.2*L* locations, where *L* is the length of the span, to balance the positive and negative moments when the precast concrete section was handled. After stripping the girders from the formwork, post-tensioning tendons were installed and grouted at the precast concrete plant to control concrete stresses during shipping and erection. These tendons are also part of the final structure design.

Next, the girders were shipped to the jobsite and erected in sequence onto the temporary falsework towers and the concrete pier caps. To erect the drop-in girders, all other girders in the superstructure unit were erected with splices cast, lid slabs poured, and partial-length continuity tendons stressed. This process required a detailed erection sequence and coordination among the contractor, precaster, and post-

tensioning subcontractor to minimize effects on the schedule.

CIP lid slabs were cast on the girders after erection and prior to post-tensioning. Casting the lid slab on site minimized girder weights for shipping, allowing for longer girders and less falsework. Before the lid slab was cast, the U-girder was an open cross section susceptible to torsional cracking. Girder sections were analyzed to ensure that torsional cracking due to placement of the lid slab would not occur. Once the lid slab cured, the torsional stiffness of the cross section increased significantly, up to 100 times that of the open section. The stiffer section is able to resist all continuity post-tensioning loading and torsion loading caused by the wet weight of the CIP deck.

After erecting drop-in girders, final closure pours were cast and continuity post-tensioning was applied in each superstructure unit. Tendons were grouted per project specifications to provide corrosion protection to the strands, to bond strands for strain compatibility behavior, and to enhance durability. Secondary diaphragms were cast at post-tensioned anchor blocks to provide protection and concrete cover for post-tensioning anchorages. The deck was cast on stay-in-place metal deck forms between girders. Finally, deck casting was sequenced to place positive moment regions first and negative moment regions last, to minimize the potential for deck cracking over piers.

Conclusion

The design and construction of the Southbound I-95 to Eastbound SR 202 Flyover Bridge is an excellent example of the versatility of precast concrete construction. Spliced, post-tensioned precast concrete designs can provide innovative and unique solutions to many bridge design challenges.

Tendon grouting is a critical component of the design and construction of this type of bridge. A strong commitment from each party to implement proper grouting specifications, grout plan submittals, quality control procedures, and quality assurance monitoring in accordance with industry specifications was an important aspect of this project. When procedures are properly implemented, spliced and grouted post-tensioned structures have proven to provide efficient designs and durable structures, and this project in Jacksonville builds on that history.

The project was a collaboration among all stakeholders to deliver a high-quality structure while addressing local traffic needs for years to come. Curved, spliced, precast concrete post-tensioned

Photo: Modjeski and Masters.

U-girders are an excellent solution for this flyover bridge structure, combining a beautiful aesthetic with a comprehensive engineered solution.

Andrew Mish is a project manager at Summit Engineering Group (a Modjeski and Masters company) in Littleton, Colo.

EDITOR'S NOTE

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AESTHETICS COMMENTARY

by Frederick Gottemoeller

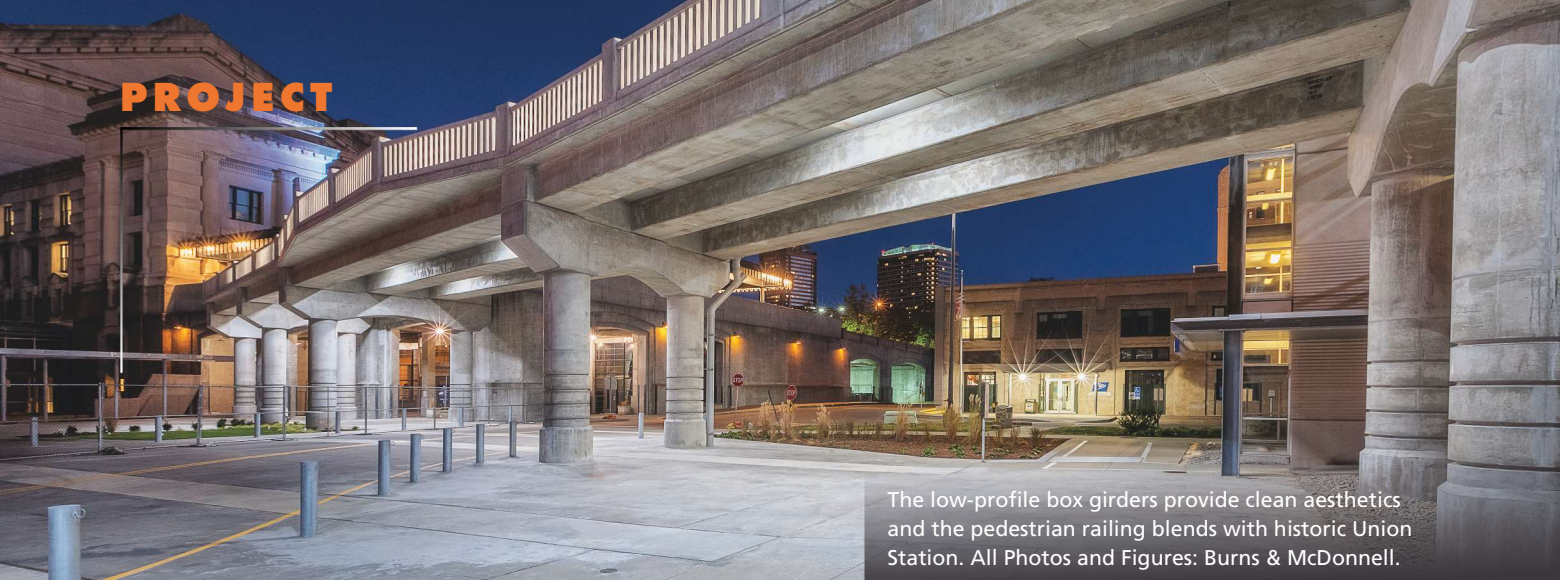
Curved flyover ramps can be impressive and exciting structures. The ramps provide a three-dimensional representation of the curved, high-speed trajectories of the vehicles passing overhead. Whether or not there are vehicles present, the ramps illustrate the dynamic function of the interchange to sort traffic into various paths. The more the lines of the structure parallel the vehicle trajectories, the more powerful this effect is. Ramps constructed as cast-in-place or segmental box girders are particularly effective. Ramps made of conventional precast concrete girders are less so, because the girder lines are broken into individual chords.

So, it is great to see a new technology, precast concrete curved U-girders, spliced and post-tensioned, solve this visual problem. The lines of the girders, curved in both the horizontal and vertical planes, follow perfectly the geometry of the ramp and thus the trajectories of the vehicles on it. The sweep of the curved girder lines is well illustrated in the photos.

Locating the piers for curved flyover ramps can be a challenge. The horizontal and vertical clearance envelopes of the roadways below limit the available locations, and the additional vertical clearance required for a pier cap placed below the girders makes the challenge even greater. The dropped pier caps also visually interrupt the curved lines of the girder edges, diminishing the effect described in the previous paragraph. The designer of this flyover ramp addressed both problems by minimizing the distance the pier caps drop below the girder soffits. The visual integration of the pier caps and girders created by placing them in the same plane (more or less) makes for a seamless transition from superstructure to substructure, visually unifying the ramp. Finally, the thin pier stem attenuates the connection between the ramp and the ground, feeding a perception that the ramp itself is flying.

People know that bridges are inherently heavy structures. Designing our bridges to *appear* lighter than they really are is one way we can use our art to make bridges memorable.

Photo: Modjeski and Masters.



The low-profile box girders provide clean aesthetics and the pedestrian railing blends with historic Union Station. All Photos and Figures: Burns & McDonnell.

THE CARRIAGE PAVILION BRIDGE AT UNION STATION

by Julie Sarson, Burns & McDonnell

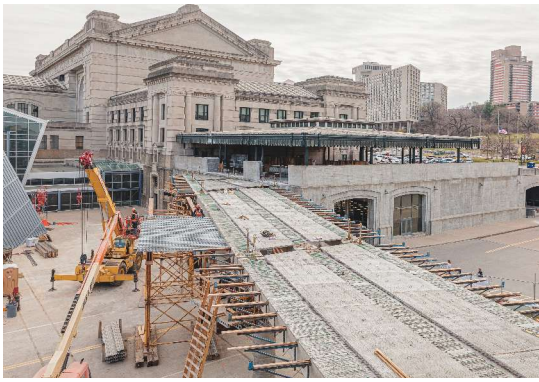
Built in 1914, Union Station Kansas City is a major attraction for culture, education, and entertainment. The facility is a historic landmark and civic asset that was extensively renovated and reopened to the public in 1999. Union Station is currently home to a science center, a planetarium, theaters, restaurants, and a busy Amtrak station. In addition, Union Station regularly hosts traveling exhibitions and community events.

Because parking and pedestrian access to this bustling facility needed improvement, Union Station Kansas City Inc. wanted a new bridge to carry vehicles and pedestrians from the front of this grand building to the third level of the existing West Yards parking structure. The bridge was constructed in 2016 as a part of the $7.8 million western expansion project. An integrated and dynamic design-build project-delivery method allowed the client to provide input about the design as construction progressed. The expansion project also included a modernization of the streetscape in the "front yard" of this majestic building, an updated eastern plaza to incorporate the terminal for Kansas City's new streetcar system, and improved bus access to the facility for school groups. With these renovations, Union Station has truly returned to its roots as a transportation hub for the region.

One of the most exciting features of the expansion project is a sprawling festival plaza for community-based events, located immediately north of the new bridge. The first outdoor extension of Science City, the science center in Union Station, is adjacent to the festival plaza and features interactive exhibits based on the concepts of simple machines. The new bridge includes a pedestrian overlook that extends toward the festival plaza and outdoor exhibit space. This overlook, designated as Kansas City's newest "selfie spot," also has stunning views of the downtown skyline to the north and the majestic National World War I Museum and Memorial to the south.

The Design Process

During the design process, Union Station's corporate, operations, and maintenance personnel provided critical input to determine the specific needs of the facility and its many events. Previously, the West Yards parking structure was only accessible by driving a circuitous route around the back of the building, nearly a half mile from the main entrance. Visitors to the facility found this parking situation



Box girders and deck form panels in place before deck reinforcement is installed.

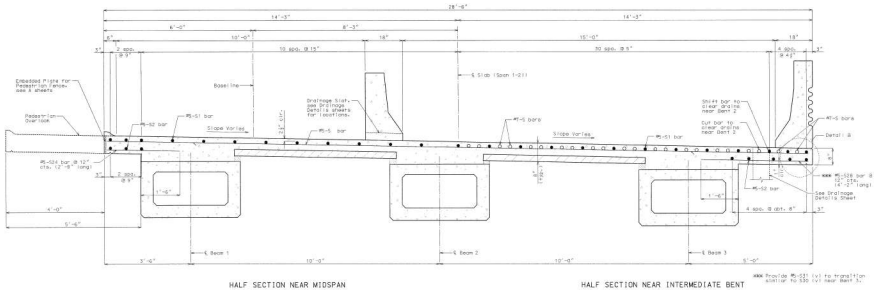
profile

THE CARRIAGE PAVILION BRIDGE AT UNION STATION / KANSAS CITY, MISSOURI

BRIDGE DESIGN ENGINEER AND DESIGN BUILDER: Burns & McDonnell, Kansas City, Mo.

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

PRECASTER: Coreslab Structures (Kansas), Kansas City, Kans. (box girders and deck form panels), and Coreslab Structures (Missouri), Marshall, Mo. (railing)—PCI-certified producers



Cross section of bridge.

to be frustrating, particularly when attending large events with a specific start time. In addition, once parked in the four-level structure, pedestrians had to travel down to ground level, cross the north lot and a local street, enter the back of the building, and take an escalator up before finally reaching the building's Grand Hall. Union Station's management wanted to improve access from the parking structure to the building and make the pedestrian approach part of the overall visitor experience.

Located at the west end of the Union Station building, the Carriage Pavilion and its roof structure were included in the 1999 renovation. This area was once used by horse-drawn carriages to drop off passengers at the Grand Hall. In more recent years, the Carriage Pavilion had been used by delivery trucks serving the post office within the building. As part of the expansion project, this area has once again become a passenger drop-off site, and it also allows vehicles to access the bridge and parking structure directly from the front of the building. The traffic crunch for major events has been alleviated with the additional entrance on the third level of the parking structure.

Specific pedestrian needs have also been addressed with the new bridge structure. The barrier-separated pedestrian path is 10 ft wide to allow ample room for families with strollers visiting the attractions. Visitors can now park and walk into the Grand Hall at the same level, which has greatly improved the pedestrian experience. In addition, a 4-ft-wide overlook juts out from the path at the center of the bridge, to provide a location to stop and take in the 360-degree view of Kansas City.

The span arrangement for the bridge was controlled by horizontal clearance to the local access road and was also set to frame the existing arches at the base of the Carriage Pavilion, resulting in spans of approximately 33, 33, 75, and 57 ft. Prestressed concrete box girders were selected for the superstructure system. These were preferred over steel girders or concrete I-girders because of their clean, low profile and because a "heavy" structure was desired to complement the aesthetic of the massive Union Station building.

Also, because this bridge is located in an urban environment, Union Station's management required a "pigeon-proof" structure with no ledges, crevices, or other nesting spots that would attract birds. Traditional cast-in-place concrete diaphragms at the pier caps to fully enclose the ends of the precast concrete box girders were the cost-effective and clean-lined solution.

Fabrication and Installation of Precast Concrete Components

The 27-in.-deep, 48-in.-wide box girders were fabricated at a local precast plant. Eleven girders ranging in length from 31 ft 0 in. to 74 ft 1 in. were required for the project. The bridge design engineers worked closely with the precaster to simplify and economize the box girder design, such as duplicating strand

Erection of a box girder in a tight space.

UNION STATION KANSAS CITY INC., OWNER

BRIDGE DESCRIPTION: Pedestrian and vehicular bridge with unusual geometry constructed using spread prestressed concrete box girders with precast deck panels and railings. The length of the four-span bridge is approximately 207 ft, the distance between the historic building and parking garage.

STRUCTURAL COMPONENTS: Prestressed concrete box girders with 3-in.-thick precast, prestressed concrete deck panel forms, 15 precast concrete rail panels (193 linear ft total), 11 prestressed box beams (556 linear ft total), 43 prestressed panels (2300 ft^2 total), and precast concrete decorative pedestrian railing

BRIDGE CONSTRUCTION COST: $1.2 million

Complex geometry at the Carriage Pavilion end of the bridge required a high level of detail for fabricating box girders and deck form panels.

patterns to allow multiple girders to be cast in one bed. Prestressing strands were extended and bent up at the ends of the boxes to provide connections to the cast-in-place diaphragms. The boxes were cast with square ends, and the cast-in-place diaphragms were meticulously detailed to avoid conflicts at the ends of the box girders.

The box girders were shipped only 10 miles from the fabrication plant to the Union Station project site where they were erected on the bents. The girders were seated on plain neoprene bearing pads. The biggest lift was about 31 tons, which was easily handled by the equipment on the small site.

Precast concrete deck form panels were selected to be used in the superstructure system to speed construction. Again, close coordination with the precast concrete producer ensured that the panels fit perfectly with the flared and skewed box girder framing near the Carriage Pavilion. Panels slightly wider than standard panel widths were allowed because of the reduced vehicular wheel loading. Deck panels are typically designed for HL-93 wheel loads. However, the design loading for the Union Station bridge was a 100-lb/ft^2 pedestrian loading, a 64-lb/ft^2 vehicular loading, or an H-5 maintenance vehicle which has an 8-kip axle loading, and tended to control the design of the slab, precast concrete panels, and shorter box girders. This design loading also allowed for snowplow equipment or other light maintenance vehicles to access the bridge and for pedestrians to occupy the full bridge width, as for a mass exit from a large event at Union Station.

The framing and overall geometric control for the bridge were complicated. Unlike a typical highway or railroad bridge, there was no established stationing or obvious tie to set the horizontal control. The bridge was detailed, fabricated, and constructed using spatial coordinates to locate the nine drilled shafts. This approach was unique but manageable. A construction baseline was established from these coordinates, using a line parallel to the northernmost drilled shafts and the north fascia of the bridge. This baseline was used to set the geometry for the box girders and precast concrete deck form panels. The precaster produced shop drawings and fabricated the girders and deck panels using this baseline, ensuring a perfect fit into the framing system.

A precast concrete pedestrian railing was desired for its smoother and more consistent finish. The rail panels were fabricated in lengths up to 15 ft and were installed at the north slab fascia between cast-in-place concrete pilasters. A precaster fabricated the rail for the panels and, as with the box girders, close coordination of the geometrics was critical. The metal forms for the panels were custom crafted in the precast producer's plant, and the spaces between the balusters were formed with expanded polystyrene. The rail panels were reinforced with epoxy-coated steel and designed for pedestrian loading.

Summary

The bridge structure brings a "heavy" but clean and low-profile aesthetic to the surrounding area, complementing both the majestic historic building and the new north festival plaza and outdoor exhibit space. As endorsed by Union Station's management, "the new Union Station Carriage Pavilion Bridge…is both an engineering marvel and aesthetic masterpiece. A mix of high-function, historic reference, and physical beauty, the bridge immediately solved a long-standing and significant customer experience challenge for the station…moving volumes of pedestrian and vehicular traffic intuitively in and out of our massive historic campus with ease. This cornerstone component of our Western Expansion Project was validated by our guests within the first fifteen minutes of opening, and every day since. In a most literal sense, it's as if the new bridge were always meant to be," said George Guastello II, president and CEO of Union Station Kansas City Inc.

Julie Sarson is the section manager for bridge design at Burns & McDonnell in Kansas City, Mo.

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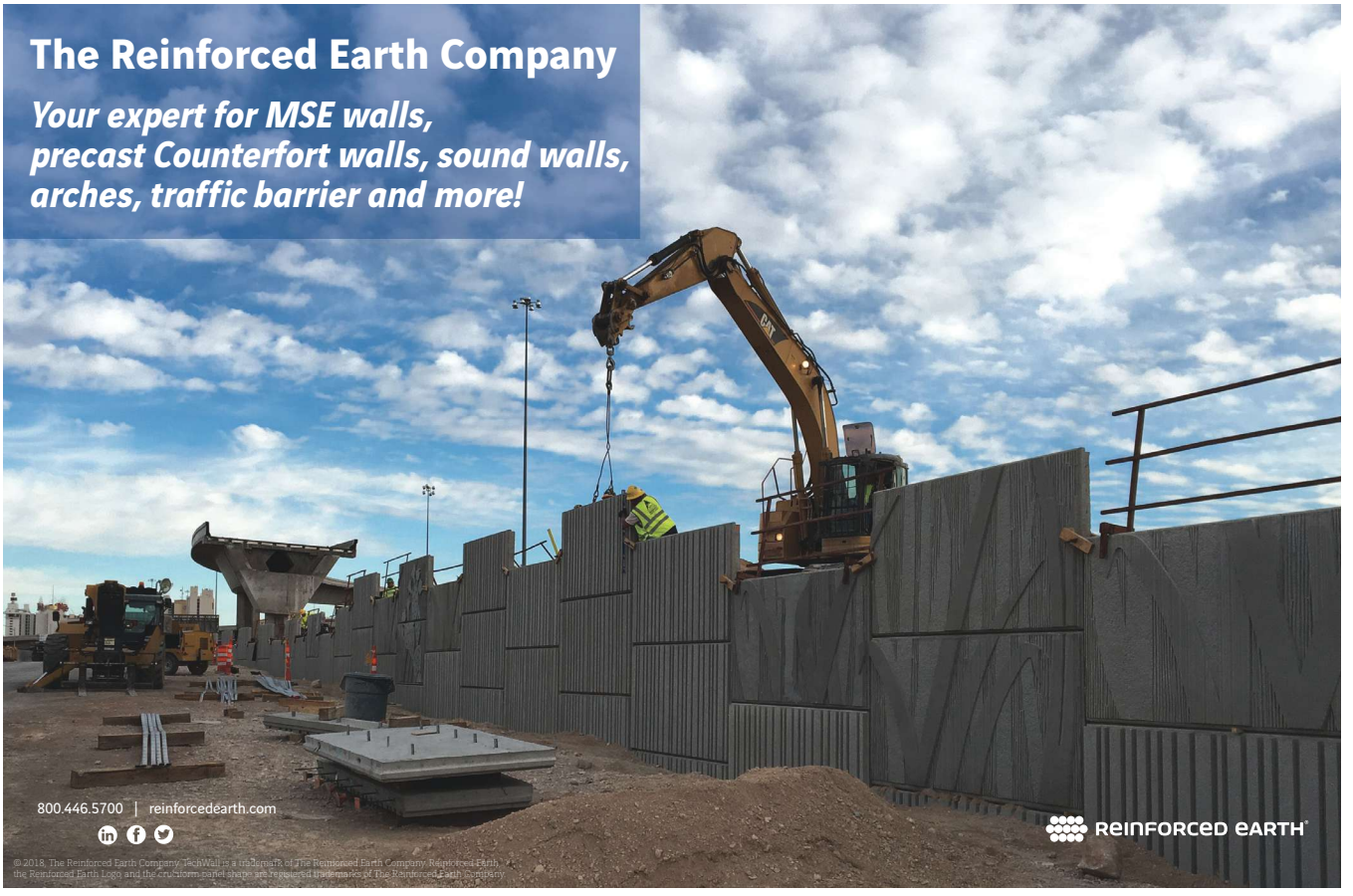

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Precast Concrete Pier Caps Aid Construction of Jacksonville Flyover Bridge with Tight Site Conditions

by Andrew Mish, Summit Engineering Group (a Modjeski and Masters company)

In September 2017, the Southbound Interstate 95 (I-95) to Eastbound State Road 202 (SR 202; also known as J. Turner Butler Boulevard) Flyover Bridge was opened to traffic in Jacksonville, Fla. The structure allows for a continuous flow of traffic through the interchange and provides a significant upgrade to the previous configuration of an off ramp with a traffic light, which led to traffic backups of a mile or more on I-95 during peak travel times.

Among the many challenges faced during the design-build process were the constrained jobsite conditions due to the heavy traffic volume on each roadway at the interchange. In just seven spans, this bridge has three major traffic crossings in an interchange that carries more than 200,000 vehicles per day. The Florida Department of Transportation (FDOT) required that all lanes remain open for the duration of construction and permitted only nighttime traffic closures, which limited construction operations to a maximum of 8 hours per day. A Project Profile article, "Southbound Interstate 95 to Eastbound State Road 202 (J. Turner Butler Boulevard) Flyover," appears in this issue of *ASPIRE*® on page 26; this article focuses on the precast concrete pier caps.

Precast Concrete Pier Caps Provide Construction Solution

With all lanes open to traffic during construction, four of the six interior piers were adjacent to active traffic as the bridge was built. This situation eliminated the possibility of the typical cast-in-place (CIP) pier caps because the shoring would interfere with traffic. Additionally, any solution needed to provide at least 16 ft 6 in. of vertical clearance. Precast concrete pier caps ultimately provided the best solution.

The contractor chose to fabricate the pier caps on site, but away from traffic. The minimum clearance was easily maintained, with the bottom of the precast concrete cap at least 17 ft 6 in. above the roadway. Additionally, the precast concrete caps were used to support girders during construction, minimizing the amount of temporary falsework required for the project.

Precast Concrete Pier Cap Design

The design of the precast concrete pier caps focused on a time-dependent, staged-construction analysis. This approach allowed the designer to ensure that the caps would perform as intended and meet all FDOT and American Association of State Highway and Transportation Officials' design criteria through each stage of construction and the full life of the structure. Loadings at each stage were considered, and time-dependent effects over the life of the structure were analyzed and included in the design.

The precast concrete caps were designed to be handled and erected as mildly reinforced components prior to the application of any post-tensioning. Designing the caps this way allowed the contractor flexibility in scheduling the erection of the caps and their phased post-tensioning.

Column-to-Cap Connection

The column-to-cap connection is one of the most important and interesting aspects of the design. The connection needed to transmit out-of-balance loadings during girder erection and work in concert with the CIP diaphragms to transfer all composite loads to the column. Each interior pier was designed with a single 7-ft by 4-ft column. The precast concrete cap was constructed with a full-depth vertical blockout that is 1 in. larger than the column cross-section dimensions. All the reinforcement from the column projected through the blockout and was developed into the CIP diaphragm.

Steel channels with welded studs form shear keys as part of the column-to-cap connection. Photo: Modjeski and Masters.

Within the blockout, four rows of steel channels (C6) were installed to create four continuous shear keys around the perimeter of the blockout. The pier cap was erected by threading it over the column reinforcement and bearing on temporary support brackets. Once it was in place, 10-in.-long shear studs were welded to the C6 channels and the blockout was cast with concrete that was the same class as the column concrete. The governing design condition during construction was the out-of-balance loading that occurred when the first girder was erected onto the pier cap.

Multiphase Post-Tensioning

The staged post-tensioning is another important aspect of the design. Each precast concrete cap was designed with

four post-tensioning tendons with twelve 0.6-in.-diameter, 270-ksi strands each. All four tendons are located at the top of the section to provide negative moment reinforcement and control stresses. The tendons in the caps were tensioned in two phases to accommodate multiple loading conditions through several stages of construction. After the column-to-cap connection concrete was cast and cured, the first two tendons were tensioned and grouted. Next, the precast concrete girders were erected and the final two tendons in the precast concrete cap were tensioned and grouted.

During the design review process, the design team and FDOT discussed whether the CIP column-to-cap connection would behave in a fully composite fashion with the cap. To account for the range of various possible behaviors, the designer bounded the solution by considering both fully composite action and zero-composite action at the connection. This approach gave the owner confidence in the construction method. The phased post-tensioning was designed to work with both solutions.

Diaphragm Composite Action

After erecting the pier girders, the integral diaphragm was cast. The CIP diaphragm was designed to act compositely with the precast concrete pier cap. To ensure composite action, the tops of the precast concrete caps were roughened to ¼-in. amplitude and reinforcement projected from the cap into the diaphragm. Both post-tensioning tendons and the reinforcing bar projected through sleeves in the girder webs to tie the diaphragm and girder together, developing integral action for the final design loadings. The diaphragm was designed with conventional reinforcement and three post-tensioning tendons with twelve 0.6-in.-diameter, 270-ksi strands each, which were tensioned prior to casting the deck and would resist the noncomposite dead load of the wet concrete deck as well as the composite dead and live loads of the final structure.

Conclusion

By using precast concrete pier caps in the design of the Southbound I-95 to Eastbound SR 202 Flyover Bridge, the designer and contractor overcame significant issues during construction. The caps were designed as a complementary piece of the structure that helped enhance the aesthetics of the bridge, and they were an integral part of the collaborative process that made this project a success.

EDITOR'S NOTE

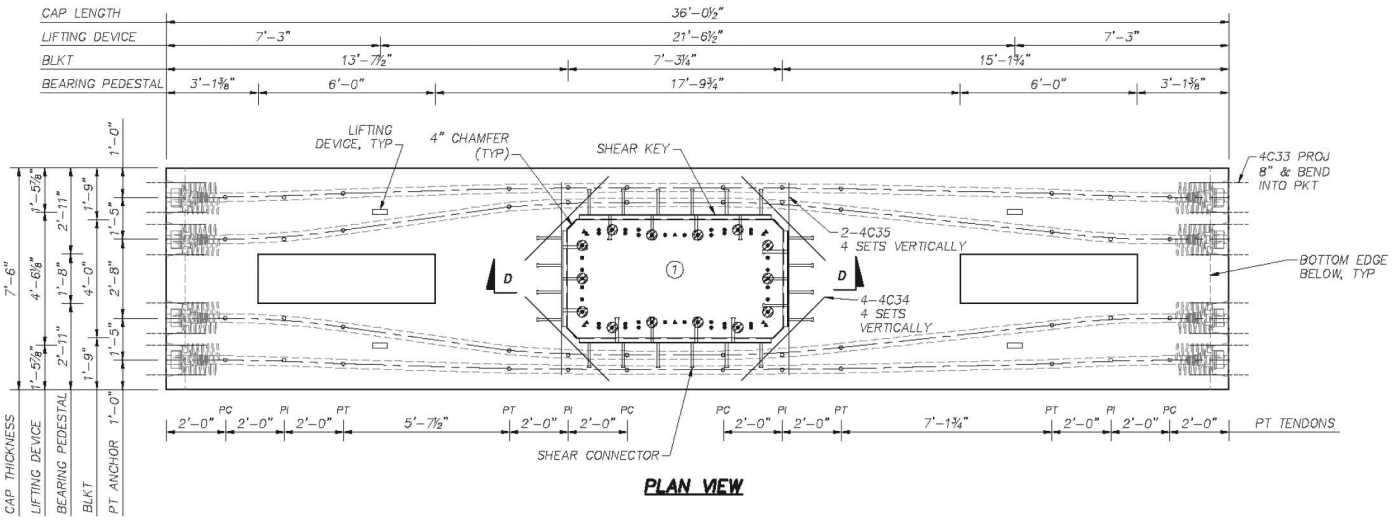
A version of this project article was originally published by Bridge Design & Engineering *magazine (www.bridgeweb.com) in* Bd&e | *ISSUE 88 | 2017.* ASPIRE*'s editors have received permission to reprint in whole or in part this article.*

Design Stages of the Precast Concrete Pier Caps

The design stages of the precast concrete pier cap were:

- Stage 1: Handling and erection of the cap as a mildly reinforced component
- Stage 2: Installing and casting of the cast-in-place (CIP) column-to-cap connection
- Stage 3: Phase 1 post-tensioning of the pier cap including tendon grouting
- Stage 4: Erection of precast concrete curved, spliced pier girders considering out-of-balance loading with only the first girder erected
- Stage 5: Phase 2 post-tensioning of the pier cap including tendon grouting
- Stage 6: Casting of the CIP diaphragm for composite action with the precast concrete pier cap
- Stage 7: Applying post-tensioning to the CIP diaphragm/cap for composite action
- Stage 8: Erection of drop-in girders and completion of longitudinal post-tensioning of the structure
- Stage 9: Casting of the CIP deck
- Stage 10: Applying composite dead loads
- Stage 11: Aging of the structure to 30 years to account for time-dependent effects
- Stage 12: Applying vehicle live loads

Andrew Mish is a project manager at Summit Engineering Group (a Modjeski and Masters company) in Littleton, Colo.



Plan view of the precast concrete pier cap showing the column blockout, horizontal post-tensioning tendon layout, and shear key. Figure: Modjeski and Masters.

Educating Students

about the Proper Use and Interpretation of Design Aids and Software

by Dr. Andrea Schokker, University of Minnesota Duluth

As engineering professors, we are responsible for giving students the background and theory they need as well as acquainting them with the design aids and tools of the profession. Design aids and software are critical to a practicing engineer, but, as with any tool, they must be used for the applications for which they were designed.

I want my students to be ready to step into their first engineering jobs with as much practical understanding as possible. However, I also want to make sure we have done a good job building a base of knowledge, including critical and innovative thinking, so they can go beyond the "cookbook" approach (or, as one of my professors used to say, "So you can design more than a one-bay chicken coop"!).

Teaching engineering judgment alongside the design process ensures that our students never just accept an answer blindly. I remember sitting in a Master's thesis defense early in my career where a colleague's student presented his findings on a purely computational project. He showed results that were consistently huge (several feet thick) for a fairly short-span concrete slab. I asked him if that seemed reasonable, and he said, "It's right because I got it from the computer." I knew then and there that I could not allow any student that came through one of my classes or my research groups to have that kind of dangerous view.

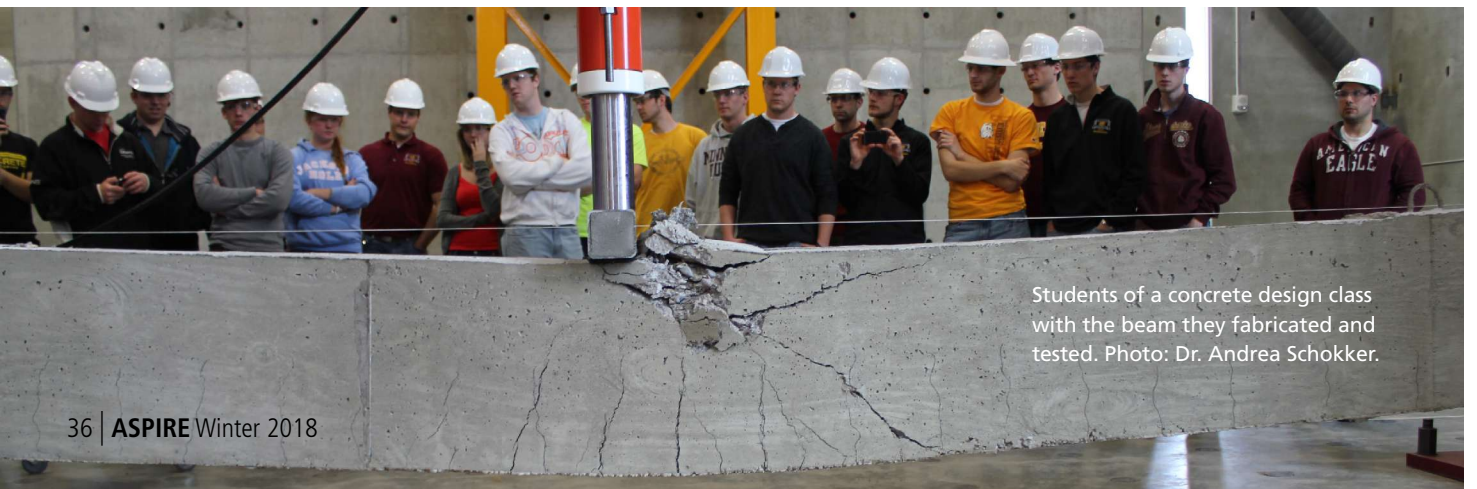
My approach is to move students into the use of design tools early in their design classes, while simultaneously challenging them with questions about the assumptions used in the process. We often use design aids and software to work on problems, and then I ask for a hand calculation for comparison. My students always know my next questions will be, "Does your hand calculation match the value from the table or computer output? Why or why not? What assumptions were made?"

Likewise, I spend time showing them the steps I use when looking at computer output. Today's programs can show results in a highly visible format, which enables the engineer to catch potential problems more quickly than when scrolling through a list of numerical output on the screen (as I remember doing with the early programs). Today's students have an inherent trust in computers, which means it is important to help them understand that "junk in equals junk out" is a major source of errors and that the way to check the input is to be able to judge the reasonableness of the output.

I tell them that I always start with a plot of the input (are the loads in the right direction and where I want them?) and then go to a deflection diagram rather than other output (does the shape and magnitude make sense?). I also teach them to consider the bounds or extremes on a solution by reducing it to a basic problem that they can do quickly by hand or in their heads to see whether the order of magnitude is reasonable. In our curriculum, we have also incorporated both small- and large-scale demonstrations to help students visualize structural behavior and to compare laboratory results to hand calculations and design aids.

Engineering judgment comes from years of experience, but its development can also be jump-started by ensuring that students realize that no design table or software is magic. When engineers use a tool, they must understand how it was developed or, at the very least, the assumptions that are built into it. They also need a way to do some basic checks of magnitude of the solution. I emphasize that design aids and software are a great starting point, but one's education as an engineer is vital for true problem solving and final design. In our field of structural engineering, the point of life safety is often one I use to drive home the significance of critical-thinking skills. In class, blindly accepting results may affect a student's grade but, in the profession, that approach might mean significant economic loss or, much worse, loss of life.

Our students will have much to learn on their first jobs, but I think a good professor understands that the educator's duty is to ensure a strong base of knowledge and an understanding of both how to use tools as well as their limitations.



Students of a concrete design class with the beam they fabricated and tested. Photo: Dr. Andrea Schokker.

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The Franklin Avenue Bridge: Investigation and Rehabilitation Design

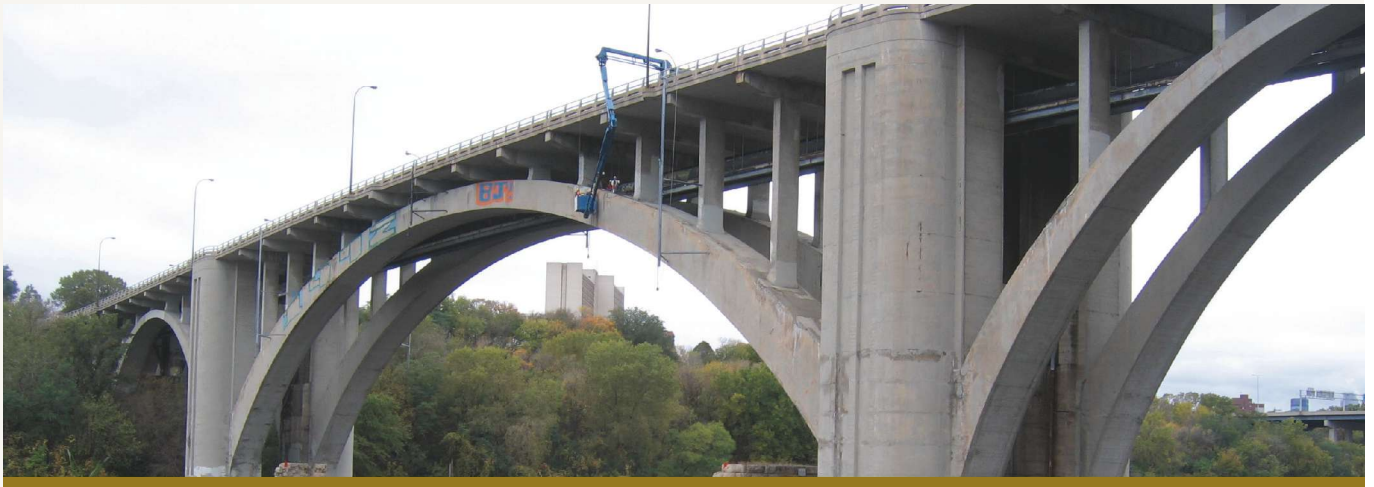
by John S. Lawler and Arne P. Johnson, Wiss, Janney, Elstner Associates Inc.; Dan Enser, HNTB; and Paul Backer, Hennepin County Transportation Department

The Franklin Avenue Bridge, constructed from 1919 to 1923 in Minneapolis, Minn., and listed in the National Register of Historic Places, crosses the Mississippi River with five open-spandrel, concrete arches. During the bridge's nearly 100-year history, harsh winters and aggressive deicing operations have resulted in advanced deterioration. Beginning with a condition investigation in 2007 and culminating in construction slated for completion in 2017, a rehabilitation project has been executed to restore this historically important structure. This Concrete Bridge Preservation article focuses on the investigation and rehabilitation design; an article[1] in the Summer 2017 issue of *ASPIRE*® focused on the structural analysis and the accelerated bridge construction methods used to replace the deck, cap beams, and railing. Additional details about this project can also be found in two articles published in *Concrete International*.[2,3]

The bridge spans consist of two parallel arch ribs ranging from 55 to 400 ft in length. The bridge has a total of five spans, an overall length of 1014 ft, and a 66-ft 4-in.-wide deck. The concrete arch ribs are reinforced using the Melan system—steel trusses composed of double-angle chords connected with riveted steel gusset plates and diagonal crossbraces. The steel trusses were erected between the piers, and then concrete was cast around the trusses forming the arch rib. No conventional reinforcement was included in the arch ribs. They were reinforced by the embedded trusses only. The historical concrete mixture incorporated gap-graded local aggregates. To accommodate the large (2½ in.), angular coarse aggregate, a high water-cement ratio (*w/c*) of about 0.50 was required in the non-air-entrained concrete mixture.

Investigation

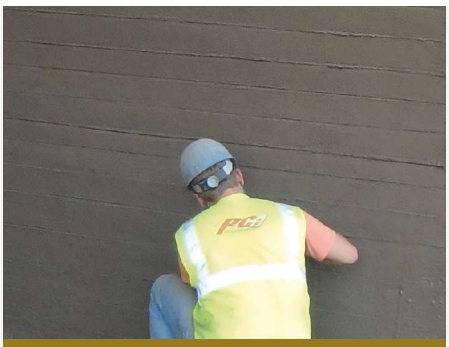
The rehabilitation process began with comprehensive investigation of the condition, performance, and historic importance of the structure. A follow-up assessment was conducted during the repair design phase to refine the repair approach and update estimates of repair quantities. The scope of both condition assessments consisted of an overall visual examination of the bridge and subsequent detailed surveys, and nondestructive testing and sampling of materials at representative areas.



Franklin Avenue Bridge during condition investigation by snooper truck. Photo: WJE.

Concrete deterioration and reinforcement corrosion below deck expansion joints. Photo: WJE.

Close-up view of same pier showing loss of concrete cover at pier corner. Photo: WJE.



Applying board-form finish to dry-method shotcrete repair on the underside of an arch rib. Photo: HNTB.

The assessments identified widespread concrete deterioration in the original concrete piers, abutments, and arch ribs to a depths as great as 22 in. below the surface, as well as longitudinal cracking along the top and bottom surfaces of the arch ribs (generally aligned with the upturned legs of the embedded steel angles). Testing showed that the causes of the deterioration were primarily chloride-related corrosion of the embedded trusses and conventional reinforcement, long-term exposure to moisture, and freezing-and-thawing cycles.

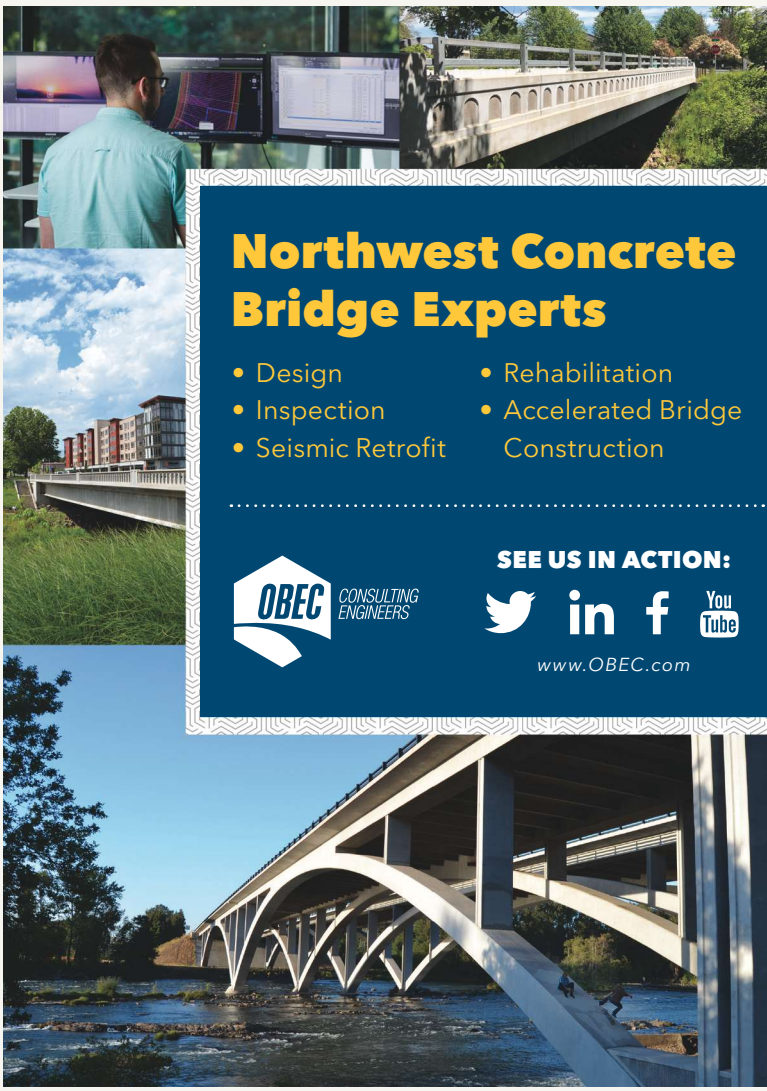
The deterioration in the various bridge elements was largely determined by their exposure to chloride-laden water from deicing salts leaking through expansion joints or by drainage of water onto the concrete surfaces. For example, the deck soffit, cap beams, and some of the spandrel columns located below expansion joints exhibited widespread and sometimes advanced delamination, spalling, and corrosion of embedded reinforcement due to chloride contamination of the concrete; in contrast, elements away from deck joints were in much better condition. High levels of chloride in the deck had also begun to produce corrosion-related damage.

Rehabilitation Design and Details

The investigation showed that the bridge was generally competent to support vehicle loading. However, deterioration in many of the bridge elements, particularly those located near expansion joints, along with a refined structural analysis and load rating, traffic study, historic property evaluation, and life-cycle cost analysis, prompted the following selective rehabilitation:

- complete removal and reconstruction of the deck and cap beams, with a traffic configuration of two central vehicle lanes flanked by barrier-separated pedestrian and bicycle lanes along the bridge length, and a wider four-lane roadway on the east end to transition into a challenging five-legged intersection just off the bridge;
- rehabilitation of the original historic concrete (piers, abutments, and arches) using historically sensitive, durable concrete repair methods supplemented with a water-resistant concrete coating and targeted corrosion mitigation along the arch rib corners; and
- restoration of historic features, including historic cap beams with scrolled ends, exterior ornamental barriers, light fixtures, deck fascia entablature, and re-created observation bays over the river piers.

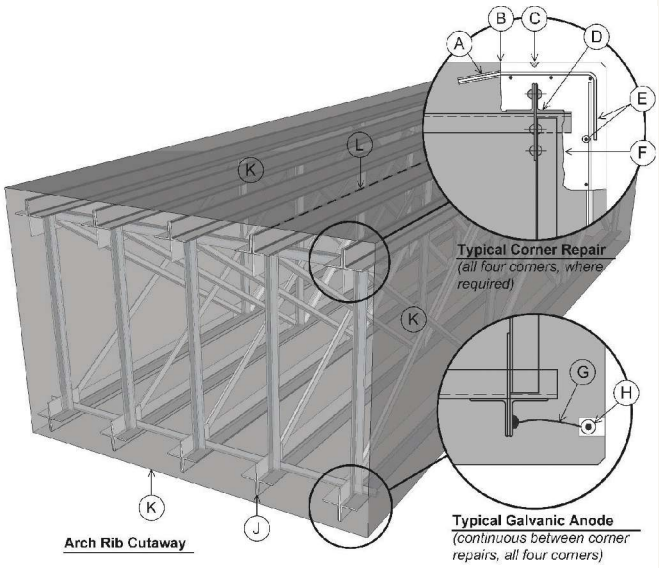
The guiding principle behind the repair design was to detail the repairs in ways that would address the root deterioration mechanisms identified while recognizing the historic sensitivity of the structure. Based on a structural analysis of thermal effects, the new deck design reduced the number



of deck expansion joints from 15 to 6, with none of the 6 joints located above a pier. This design reduces future leakage potential, which is expected to extend the life of the vulnerable historic concrete.

Concrete surface repairs were specified and detailed for all locations where delaminations and spalls were present. The specifications demanded high-quality concrete repair techniques, including perimeter saw cutting, removal to sound concrete using light chipping hammers, substrate preparation via sandblasting, sandblast cleaning and coating of exposed reinforcement, and anchorage using epoxy-grouted bars. The specifications were designed to allow the contractor to choose form-and-pour, form-and-pump, or shotcrete methods with either prepackaged or ready-mixed concrete for each type of repair. The contractor chose prepackaged dry-mix shotcrete for most repairs.

In portions of the bridge most visible to the public, the new concrete repairs were specified with a board-form finish to match the original surface texture. The new surface-coating and concrete-repair materials were colored to a light-buff color that was selected on site by the historian to be within the range of the original concrete color. Mock-ups and field trials were implemented to evaluate the contractor's materials and methods and conformance with the project specifications. The long-term durability of these concrete repairs was augmented with a film-forming coating throughout the bridge, as well as passive cathodic protection at targeted locations in the corners of the arch ribs.



Cutaway view of arch rib showing Melan truss reinforcement and typical concrete repairs. Figure: WJE.

A – epoxy-grouted dowels for anchorage;
B – saw cuts at repair perimeter;
C – tooled joint with sealant;
D – clean and coat existing steel;
E – crack-control reinforcement;
F – properly prepared, sound concrete substrate;
G – intermittent slots and wire connections to existing steel;
H – continuous zinc anode in sawcut slot;
J – Melan truss reinforcement;
K – typical surface repairs;
L – grout and seal crack

Several key factors contributed to the success of the project:

- a thorough, early investigation accurately identified the deterioration mechanisms and allowed for selection of appropriately targeted rehabilitation alternatives;
- due consideration of historic preservation principles led to the decision to protect vulnerable historic fabric by using a high-performance, water-resistant, opaque concrete coating;
- cathodic protection systems were targeted to slow corrosion at the most vulnerable locations and detailed to be less visible from the ground;
- step-by-step mock-ups validated the color, texture, and quality of the repair methods before full-scale implementation; and
- historic concrete assessment and rehabilitation experts collaborated with bridge analysis and design experts; historic preservation agencies; county engineers, technicians and inspectors; community stakeholders; and a contractor experienced in historic concrete repair.

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Arne P. Johnson, principal, was Wiss, Janney, Elstner Associates' project manager for this project, and he was assisted by John S. Lawler, associate principal at Wiss, Janney, Elstner Associates, both in Northbrook, Ill. Dan Enser is a project manager with HNTB in Golden Valley, Minn. Paul Backer is a senior construction engineer with Hennepin County Transportation Department.

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Evaluation and Epoxy-Injection Repair of Cracks in Concrete

by Leo Mancs, Vector Construction

The addition of steel reinforcement to concrete in the 19th century enabled structural concrete elements to work not only in compression but also in tension, which caused cracking in tension areas. Other common causes of concrete cracking are plastic shrinkage, settlement, drying shrinkage, thermal stresses, chemical reaction (due to alkali-reactive silica or sulfates), freezing and thawing, corrosion of reinforcing steel, overload stresses, poor construction practices, and design or detailing errors.[1]

Even if concrete cracking does not affect structural performance, it can adversely affect the durability of structures by allowing chloride or carbon dioxide deep into the structural element and initiating corrosion over time. To some extent, cracking can be minimized or controlled by employing appropriate design, detailing, and construction practices and by incorporating advanced construction materials into new concrete structures.[2]

ACI 224R-01[2] Table 4.1 provides a general guideline for reasonable crack widths for reinforced concrete under service loads for new construction. Acceptable crack widths range from 0.004 in. (0.1 mm) to 0.016 in. (0.41 mm), with smaller widths for concrete in wet or aggressive environments and larger crack widths for drier exposures. It is up to the specifier to use sound engineering judgment along with applicable standards to determine crack widths that may lead to a loss in functionality of the concrete structure.

For a concrete structure, once the allowable crack width is established and cracks are identified, their widths and depths and the cause of cracking should be determined. The width of cracks can be measured to a precision of 0.001 in. (0.025 mm) by using crack gauge cards or pocket microscopes. It is important that the actual width of the crack is measured at a clean and straight location along the crack and that the measurement does not include the width of chipped or worn edges of the crack. To determine the depth and cause of cracking, core samples can be taken and, if subjected to petrographic testing, analyzed for issues such as freeze-thaw resistance, alkali-silica reactivity, or delayed ettringite formation. The depth of cracking can also be evaluated by a nondestructive testing (NDT) method such as ultrasonic pulse velocity.

Table 4.1 Guide to reasonable* crack widths, reinforced concrete under service loads

Exposure condition	Crack width	
	in.	mm
Dry air or protective membrane	0.016	0.41
Humidity, moist air, soil	0.012	0.30
Deicing chemicals	0.007	0.18
Seawater and seawater spray, wetting and drying	0.006	0.15
Water-retaining structures†	0.004	0.10

*It should be expected that a portion of the cracks in the structure will exceed these values. With time, a significant portion can exceed these values. These are general guidelines for design to be used in conjunction with sound engineering judgement *[sic]*.
†Exclusing *[sic]* nonpressure pipes.
Note: Table 4.1, Guide to Reasonable Crack Widths, Reinforced Concrete Under Service Loads, was reproduced from ACI 224R-01 (Reapproved 2008) *Control of Cracking of Concrete Structures* with permission from the American Concrete Institute.

Crack widths can be visually measured using a gauge card (middle) or pocket microscopes. All Photos: Vector Construction.

Because the bond strength of epoxy to concrete is greater than the tensile strength of concrete, epoxy injection can restore the structural integrity of the concrete when applied to cracks 0.002 in. (0.05 mm) in width or greater. It is important to note that if the cause of cracking is corrosion of the reinforcing steel or if movement of the concrete is anticipated after repairs, epoxy injection may not be the best solution to the problem.[3]

Shallow cracks on horizontal surfaces such as bridge decks or the tops of pier caps can be repaired by gravity feed

After the surface has been cleaned, surface-mounted injection ports are installed. A temporary crack-sealer epoxy paste will be applied on the face of the crack between and around the ports before the injection process begins.

Epoxy injection of cracks using a dual-component pump with positive displacement and metering capabilities. The epoxy resin is delivered through two lines to the static mixer, where it is mixed and immediately discharged into the crack through the injection port.

using epoxies or high-molecular weight methacrylate (HMWM). Both materials have very low viscosities (less than 100 cps) and low surface tensions; therefore, they can penetrate cracks with widths as narrow as 0.002 in. (0.05 mm) without the resin being pressurized.[4]

Epoxy-injection resins that are used for structural crack repairs conform to the requirements of ASTM C881,[5] Type IV, and have appropriate viscosities for the crack widths and degree of confinement of the resin.[6] Wider cracks that cannot be sealed on all sides require a higher viscosity (paste) injection material, whereas most cracks that can be sufficiently sealed are injected with epoxies at viscosities of 300 to 600 cps at room temperature. For applications at temperatures less than 60°F (15°C) and for fine cracks less than 0.01 in. (0.25 mm) in width, the viscosity of the epoxy needs to be lower, in the 150 to 225 cps range.

Crack injection can be completed using air guns, hand-actuated delivery systems, spring- or balloon-actuated capsules, or single- or dual-component injection electric or air-driven pumps.

For consistent performance on large or critical projects, use of a dual-component pump with positive displacement and metering capabilities is recommended. After calibration, the epoxy materials are metered by the pump and mixed to the proper ratio in a static mixer just before entering the crack.

Typically, wire brushing and vacuuming the crack surface on a 2-in.-wide (50-mm-wide) strip along the crack is sufficient for surface preparation. In some cases, pressure washing, grinding, or V-grooving may be needed to access clogged cracks.

Surface-mounted injection ports are adequate for injecting most cracks. Where the surface of the crack is blocked or the width of the cracks is $^1/_8$ in. (3 mm) or larger, plastic tubing ports are directly inserted in open cracks or sealed in holes drilled to intersect the cracks. The injection ports are typically installed at a spacing that is equal to or greater than the measured depth of the crack.

Once the injection ports are installed, a temporary crack-sealer epoxy paste is applied on the face of the crack between and around the ports. To contain the epoxy resin in the crack until it hardens, it is a good practice to seal cracks on all sides of the concrete element.

Injection of epoxy always begins at the lowest elevation. Once the epoxy emerges at the next higher port, the current port is capped and the injection is continued from the port where the epoxy emerged. The process continues in this manner until all ports are injected. Typical injection pressures are between 50 to 100 psi (350 to 700 kPa), with very fine cracks requiring pressures of 200 psi (1.4 MPa) or higher, provided that the crack seal is not damaged by the high pressure. Raising ambient and resin temperatures can lower resin viscosity and require less pressure. Minor epoxy leaks through hairline cracks can be sealed using paraffin wax. Once the crack sealant has hardened sufficiently, the crack-sealer epoxy paste is usually removed from the surface of the concrete according to manufacturer's recommendations.

Epoxy emerging from port and hairline crack not previously visible.

Quality assurance/control measures to ensure that cracks are sufficiently repaired may include visual observation of the injection process, laboratory testing of mixed epoxy, testing the injection equipment for mix ratio under pressure, evaluation of cores sampled through the injected crack, and testing across the repaired cracks using NDT methods such as ultrasonic pulse velocity, impact echo, or spectral analysis of surface waves.[7]

Specialist concrete repair contractors with experience in the epoxy-injection process and manufacturers of injection resins and equipment are valuable resources for providing means, methods, and training for epoxy injection.

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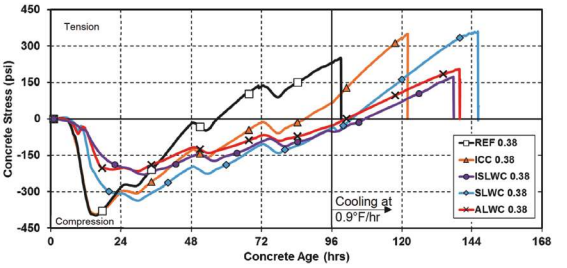
Drying specimens (Tourney)



Restrained stress development for all 0.38 *w/cm* concretes (Auburn University)

New research reports now available

ESCSI is pleased to announce that two new studies have recently been completed and the reports are now available on escsi.org.

Tourney Consulting Group recently completed a study to determine the effects of lightweight aggregates on transport properties and other durability related properties of concrete. Transport properties are used in several service life programs. Their study confirmed that the time to corrosion in a reinforced concrete structure increases by approximately 25% when a lightweight concrete mixtures are used compared to a comparable mixture with normalweight aggregates. The study also found that some lightweight concrete mixtures increased time to corrosion by a factor of two to three.

Auburn University recently completed a study on the effect of using several types of lightweight aggregate concrete on the early-age cracking tendency of mass concrete. Laboratory testing simulated the edge of an 8×8 ft mass concrete column. The study found that the use of lightweight aggregates is beneficial to control early-age cracking because it reduces autogenous shrinkage, lowers the modulus of elasticity, and lowers the coefficient of thermal expansion. The presence of LWA in concrete was also found to delay the time to cracking.

Watch for articles on these reports in coming issues of *ASPIRE*[SM].

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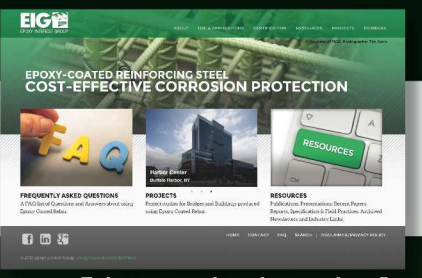

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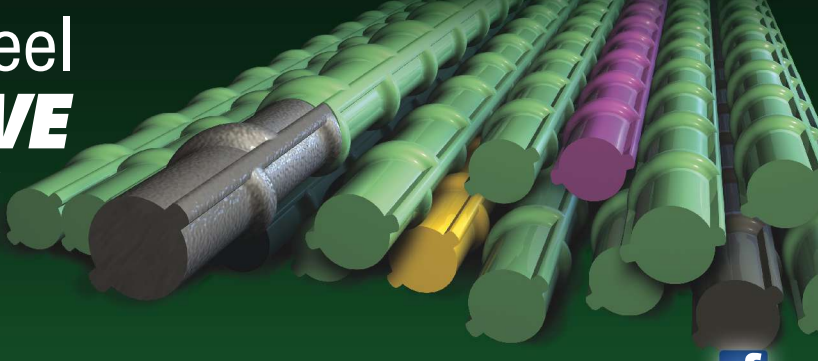

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Strut-and-Tie Modeling: What, When, Why, and How

by Reggie Holt, Federal Highway Administration

Strut-and-tie modeling (STM) is a technique that is commonly used to reduce complex states of stress in reinforced and prestressed concrete structures into a simplified truss model. STMs are made up of elements loaded uniaxially in tension (referred to as *ties*) or compression (referred to as *struts*). The intersection points of the struts and ties are called *nodes*. This simplified truss model can then be analyzed using basic statics such as the method of sections or joints. The STM method is based on the lower-bound (that is, conservative) theorem of plasticity, which ensures a safe structure. Another unique aspect of STM analysis with respect to traditional sectional analysis is that it has a unified approach that considers all force effects (moment, shear, axial) simultaneously.

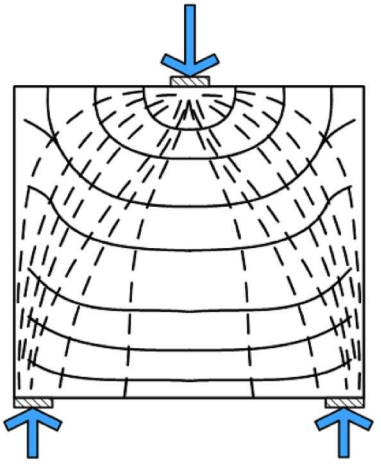

Figure 1. Complex stress trajectories within concrete element. Note: dashed lines = compression; solid lines = tension. All Figures: Federal Highway Administration.

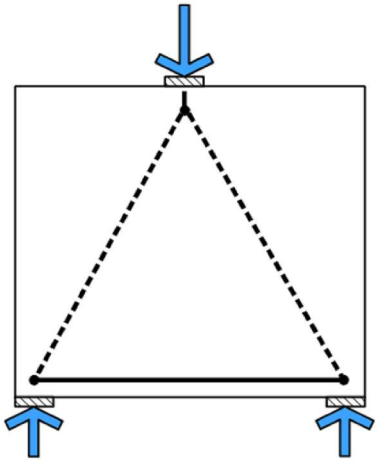

Figure 2. Strut-and-tie model. Note: dashed lines = compression; solid lines = tension.

Figures 1 and 2 show a concrete element with a complex stress profile and how STM can simplify these stresses into a truss model, respectively.

When to Use STM?

The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* classify regions within structural concrete elements into two distinct categories: B-regions or D-regions. B-regions (beam or Bernouli) are regions within the element that have linear strain profiles, to which the principles of linear-elastic beam theory apply and for which traditional sectional design is appropriate.

D-regions (disturbed or discontinuity), are regions that include concentrated loads or geometric discontinuities with strain profiles that are complex and nonlinear and therefore not appropriate for traditional sectional design. D-regions require analysis methods that can address these nonlinear strain profiles. Analysis using STM can address the stress complexities in a D-regions with a representative internal truss model that replicates the region's internal load transfer.

Figure 3 is an example of a concrete member's B- and D-regions. The AASHTO LRFD specifications include guidance on determining the extent of each region. For the element shown in Fig. 3, only the D-regions require an analysis, such as STM, that can address their nonlinear strain profiles.

Why Use STM?

STM provides designers with an easy-to-use analysis tool for D-regions that would otherwise require a more complex analysis, such as finite element analysis. Improperly designed D-region can result in in-service cracking issues. The AASHTO LRFD specifications have design limits and detailing requirements to limit problematic D-region cracking. It should be noted that using sectional design for D-regions can lead to structural elements that are substantially underdesigned.

A secondary benefit of STM is that it requires the designer to visualize and understand the internal load paths and stress fields, which, in turn, along with the STM design provisions, promote good overall element sizing and reinforcement detailing.

How to Learn More?

One of the most significant hurdles in using the STM technique is the lack of available guidance for bridge practitioners and, more specifically, guidance that follows the provisions in the AASHTO LRFD specifications. Furthermore, very few U.S. colleges include STM in their structural engineering

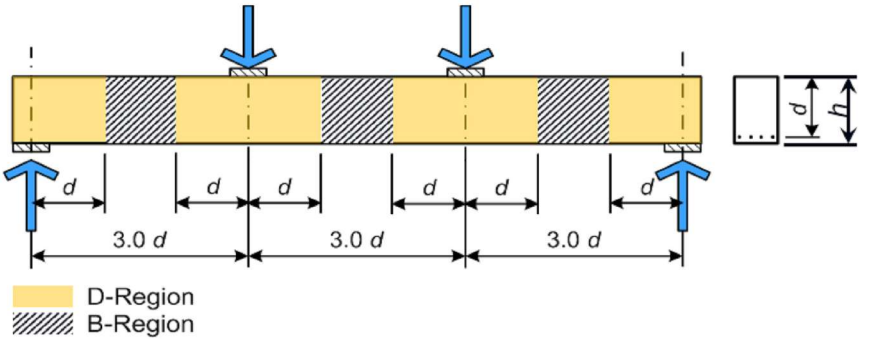

Figure 3. B- and D-regions of an example concrete beam.

curriculum, which has compounded the need for guidance. To address this gap, the Federal Highway Administration (FHWA) has developed new STM training and design examples that follow the provisions in the 8th edition of the AASHTO LRFD specifications. The FHWA training course and guidance are based on the 8th edition because AASHTO has made significant changes to the STM provisions and substantially reorganized Section 5: Concrete Structures, resulting in many changes to this section's content and article numbering.

Four comprehensive design examples are available on the FHWA bridge website (https://www.fhwa.dot.gov/bridge/concrete/nhi17071.pdf). These design examples progress in complexity and include a simply supported beam, a cantilever bent cap, an inverted-tee straddle bent, and a three-dimensional model of a drilled-shaft footing. These design examples were selected to cover as many "real-life" STM bridge scenarios as possible. These design examples are a very valuable resource within the bridge design community (Fig. 4).

The training is a one-and-a-half-day, instructor-led course delivered through the National Highway Institute (NHI). This training course will be available in the very near future. For more information, visit the NHI website (https://www.nhi.fhwa.dot.gov/home.aspx) and search for course number 130126.

Acknowledgment

FHWA acknowledges the Texas Department of Transportation (TxDOT) for its efforts and leadership in advancing the state-of-practice for strut-and-tie modeling. Much of the information used to develop the FHWA training and example problems came from completed TxDOT research, implementation, and guidance. The contributions of Dean Van Landuyt, John P. Vogel, David Hohmann, and Gregg Freeby of TxDOT and those of David Birrcher, Robin Tuchscherer, Matt Huizinga, Dean Deschenes, Chris Williams, and Oguzhan Bayrak from the Ferguson Structural Engineering Laboratory at the University of Texas at Austin have been invaluable and are gratefully acknowledged.

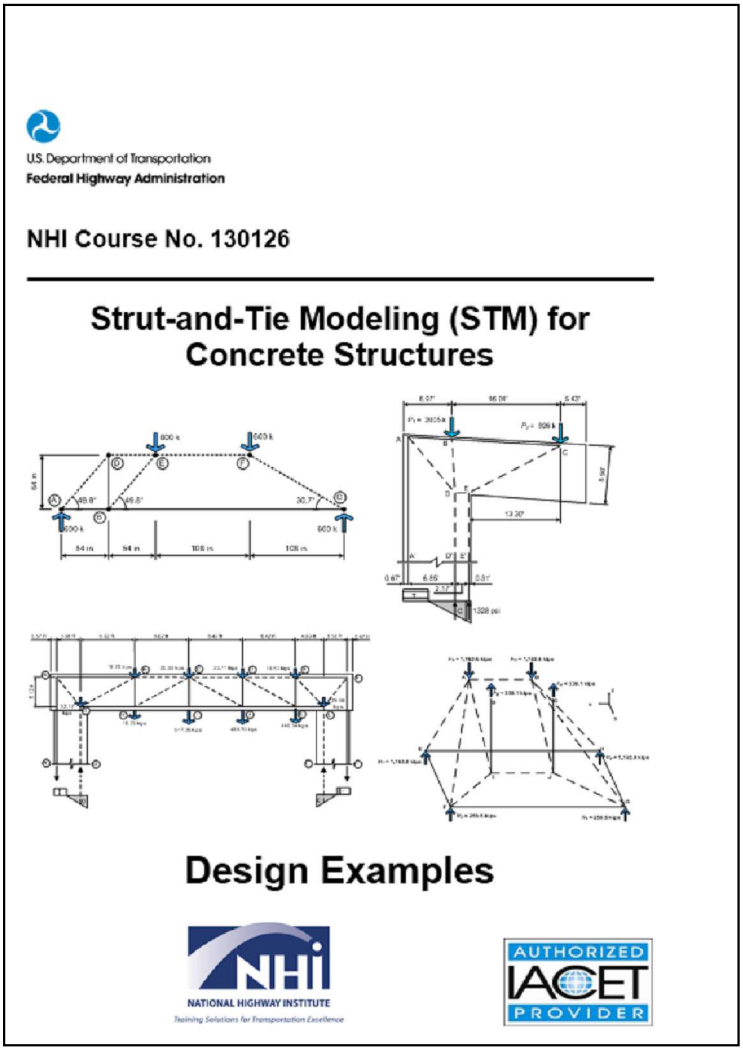

Figure 4. Cover of *Strut-and-Tie Modeling (STM) for Concrete Structures.*

What Type of Concrete Is It?

by Dr. Henry G. Russell, Henry G. Russell Inc.

Like products in the supermarket, concrete comes in various types. In case you are confused, here are some definitions from the American Concrete Institute,[1] unless marked as an American Association of State Highway and Transportation Officials (AASHTO)[2] definition.

Cast-in-place concrete — concrete placed in its final location in the structure while still in a plastic state (AASHTO definition).

Class of concrete — an arbitrary characterization of concrete of various qualities or usages, usually by compressive strength.

Concrete — mixture of hydraulic cement, aggregates, and water, with or without admixtures, fibers, or other cementitious materials.

Fiber-reinforced concrete — concrete containing dispersed, randomly oriented fibers.

Flowing concrete — a cohesive concrete mixture with a slump greater than 7½ in.

Fresh concrete — concrete that possesses enough of its original workability that it can be placed and consolidated by the intended methods.

Green concrete — concrete that has undergone final setting but not hardened appreciably.

Hardened concrete — concrete that has developed sufficient strength to serve a defined purpose or resist stipulated loading without failure.

High-early-strength concrete — concrete that, through the use of additional cement, high-early-strength cement, or admixtures, has accelerated early-age strength development.

High-performance concrete — concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices.

High-strength concrete — concrete that has a specified compressive strength for design of 8000 psi or greater.

Lean concrete — concrete of low-cementitious-material content.

Lightweight concrete — concrete containing lightweight aggregate conforming to AASHTO M 195 and having an equilibrium density not exceeding 0.135 kip/ft^3, as determined by ASTM C567 (AASHTO definition).

Monolithic concrete — concrete cast with no joints other than construction joints.

No-fines concrete — a concrete mixture containing little or no fine aggregate.

Non-air-entrained concrete — concrete in which neither an air-entraining admixture nor air-entraining cement has been used.

Normal weight concrete — concrete having an equilibrium density greater than 0.135 kip/ft^3 and a density not exceeding 0.155 kip/ft^3 (AASHTO definition).

No-slump concrete — freshly mixed concrete exhibiting a slump of less than ¼ in.

Packaged concrete — mixture of dry ingredients in packages, requiring only the addition of water to produce concrete.

Plain concrete — structural concrete with no reinforcement or with less reinforcement than the minimum amount specified for reinforced concrete in the applicable building code.

Precast concrete — concrete cast elsewhere than its final position.

Prestressed concrete — concrete components in which stresses and deformations are introduced by application of prestressing forces (AASHTO definition).

Recycled concrete — hardened concrete that has been processed for reuse, usually as aggregate.

Reinforced concrete — structural concrete containing no less than the minimum amounts of prestressing tendons or nonprestressed reinforcement specified herein (AASHTO definition).

Rich concrete — concrete of high cement content.

Self-consolidating concrete — fresh concrete that can flow around reinforcement and consolidate within formwork under its own weight without vibration.

Shotcrete — concrete placed by a high velocity pneumatic projection from a nozzle.

Shrinkage-compensating concrete — concrete containing expansive components usually based on formation of calcium sulfoaluminate (ettringite) in a mixture of calcium aluminate and gypsum.

Shrink-mixed concrete — ready-mixed concrete mixed partially in a stationary mixer and then mixed in a truck mixer.

Structural concrete — all concrete used for structural purposes (AASHTO definition).

Structural mass concrete — any large volume of concrete where special materials or procedures are required to cope with the generation of heat of hydration and attendant volume change to minimize cracking (AASHTO definition).

Underwater concrete — concrete placed underwater by tremie or other means.

Vibrated concrete — concrete consolidated by vibration during and after placing.

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Dr. Henry G. Russell is an engineering consultant and former managing technical editor of ASPIRE®.

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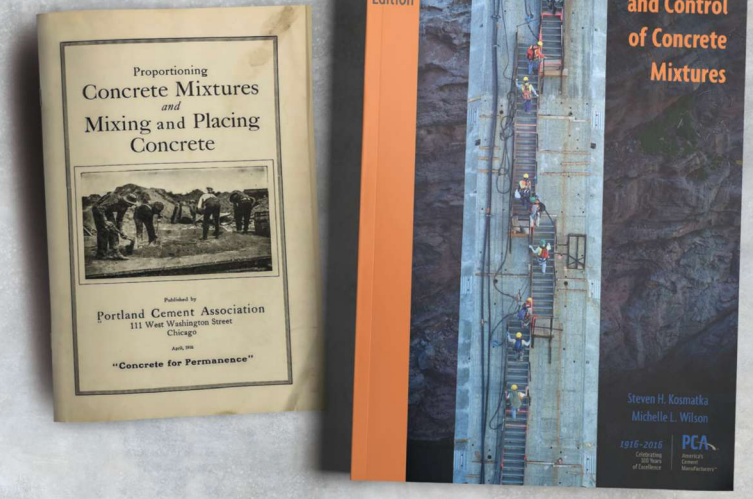

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Repurposing Prestressed Concrete Girders in Oregon

by Matthew Stucker and Dr. Tanarat Potisuk, Oregon Department of Transportation

Repurposed girders erected on Bridge 22009 of the Newberg-Dundee Bypass Project. Photo: Oregon Department of Transportation.

Citizens and businesses of Yamhill County, Ore., have been advocating for the construction of a traffic-congestion solution along Oregon Route 99 West through the towns of Newberg and Dundee for over 25 years and will soon have access to the Newberg-Dundee Bypass (see the Project Profile article in this issue that is on the same project). It is expected to significantly improve the quality of life and overall traffic flow for the region. Bridge design and construction for this first phase of the planned 11-mile bypass incorporated 112 precast, prestressed concrete girders originally produced for another Oregon project.

During construction of the Pioneer Mountain-Eddyville (PME) project, the Oregon Department of Transportation (ODOT) had to reconsider the planned bridge solution. ODOT determined that a large fill and culvert, coupled with landslide mitigation, would be a better path forward for the PME project. Because girders for the PME project had already been fabricated by Knife River Corporation's Prestressed Concrete Division, ODOT entered into an agreement to store the unused bridge girders at the company's facility while ODOT searched for an opportunity to use the fabricated girders.

With the design of the 10 bridge structures on the ND Bypass underway, using the girders from the PME project presented a unique twist to designers during the bridge design type, size, and location decision process. All 112 girders were 84-in. bulb-tee sections, and 105 of them were approximately 150 ft long. Some of the girders were originally designed for bridge spans that were located on a horizontal curve with skew; therefore, the girder lengths in the same span varied by as much as 5 ft 2 in. While all design options were considered, it was determined that all 112 repurposed girders could be efficiently used on four of the 10 bridges on the ND Bypass project.

All 112 repurposed girders could be efficiently used on four of the 10 bridges on the ND Bypass project.

Designers for the various bridges selected girders for each bridge by best fit and on a first-come, first-served basis. One bridge is located on a horizontal curve, and the other three bridges are on a tangent roadway alignment. Minor modifications to the repurposed girders were required to fit the new end-girder connection design. The last bridge designed had to incorporate girders with varying lengths, which was accommodated by introducing slight skews in two interior piers that would have otherwise been oriented perpendicular to the roadway alignment. Before transporting the girders to the new site, lifting loops were evaluated for corrosion damage because they had been exposed to the elements for 7 years.

New bridge girders for the ND Bypass would have typically cost about $3.4 million, whereas approximately $1.1 million was spent for storage, transport, placement, and adjustment of the girders originally intended for the PME project. Collaboration with project stakeholders, cost justification, and construction timing resulted in a successful girder-repurposing project.

Matthew Stucker is a structural design engineer and Dr. Tanarat Potisuk is a prestressed concrete standards engineer, both with the Oregon Department of Transportation in Salem, Ore.

Mississippi

by Justin Walker, Scott Westerfield, and Michael Flood, Mississippi Department of Transportation

Mississippi is a state built on concrete structures. Of the state's 16,596 bridges, the Mississippi Department of Transportation (MDOT) manages and maintains 5775. Approximately 88% of these bridges are constructed with concrete superstructures.

To widen and replace state-owned bridges, MDOT uses American Association of State Highway and Transportation Officials (AASHTO) prestressed concrete girder shapes along with bulb-tee girders. The locally owned bridge system relies mainly on precast concrete channel-beam bridges for short-span structures.

Mississippi has three precast, prestressed concrete facilities capable of producing voided-slab spans, AASHTO girders, Louisiana girders, Florida girders, Northeast Extreme Tee (NEXT) beams, and prestressed concrete piling. The state has two additional facilities capable of casting reinforced (nonprestressed) concrete channel beams and aesthetic panels.

A robust concrete industry, coupled with the desire to be innovative and create an active working relationship among the departments of transportation (DOTs) of the Gulf South Region, has helped keep a large variety of precast concrete elements cost-effective.

The Gulf South Precast Concrete Association (GSPCA) was founded in 1961 to promote precast, prestressed concrete elements for the transportation systems in Alabama, Louisiana, and Mississippi. In 2016, GSPCA reorganized to form PCI Gulf South, a chapter of the Precast/Prestressed Concrete Institute.

PCI Gulf South expanded its role with DOTs by forming a regional transportation committee composed of members from the Alabama, Louisiana, and Mississippi DOTs, industry, educational institutions, and consultants. Through collaboration with PCI Gulf South, MDOT continues the expansion of concrete technology and standardization today. The relationship has helped MDOT expand the use of concrete elements such as Florida I-beams (FIB),

On February 17, 2016, after a routine inspection indicated significant scour on the southeast corner of the bridge located on Robinson Road in Jackson, Miss., the bridge was closed for nearly a year while plans were developed and funding was acquired. A new bridge was constructed with precast, prestressed concrete Florida I-beams and a cast-in-place deck. It opened to traffic on September 1, 2017. All Photos: Mississippi Department of Transportation.

NEXT beams, and other pre- and post-tensioned precast concrete bridge elements. MDOT has worked with PCI Gulf South to implement use of these elements in a way that is consistent with surrounding states. This standardization has allowed MDOT to purchase these elements at much lower costs.

Long-Span Post-Tensioned Systems

Mississippi has traditionally turned to structural steel for long-span river and railroad crossings, grade separations, and bay bridges. However, because the cost of structural steel is high and the state lacks a strong steel industry with fabrication capabilities, prestressed and post-tensioned concrete systems have become the structures of choice for long spans.

On August 29, 2005, Mississippi was severely affected by one of the most devastating hurricanes to strike the Gulf Coast. Hurricane Katrina destroyed two of the state's large bascule bridges along U.S. Highway 90 in Biloxi Bay and Bay St. Louis. With replacement costs at nearly $500 million, Mississippi began developing design-build documents to replace the two bridges. This was MDOT's second design-build project after the Mississippi Legislature opened the procurement process in 2004, and the estimated cost was 100 times that of MDOT's first design-build project, the replacement of a low-traffic, rural bridge.

Under a conventional, expedited design-bid-build procurement format, MDOT expected project delivery would take between three and four years. However, design-build provided a project delivery of less than two years.

The Bay St. Louis Bridge was constructed by a joint venture of Granite Construction, Watsonville, Calif., and Archer Western (Walsh Group), Atlanta, Ga., with HNTB, Baton Rouge, La., in charge of the design as well as construction engineering and inspection (CEI) (See *ASPIRE*® Spring 2007). The Biloxi Bay Bridge was constructed by joint venture Kiewit Massman Traylor Constructors, Omaha, Neb., as the contractor and Parsons Transportation Group, Pasadena, Calif., as the designer, with Volkert in Jackson, Miss., conducting the CEI (See *ASPIRE* Winter 2012). Both bridges were completed in record time with prestressed, post-tensioned concrete girders as the superstructure elements.

Each bridge is a fixed-span high-rise structure composed of prestressed concrete bulb-tee girders with a multispan, haunched, post-tensioned main span unit. The decks are cast-in-place (CIP) concrete and contain pedestrian lanes that are large enough to double as inspection lanes for under-bridge inspection vehicles.

After being damaged beyond repair following Hurricane Katrina in August 2005, the new Biloxi Bay Bridge was completed in record time with prestressed concrete girder approach spans and haunched post-tensioned concrete girders for the main spans. The aesthetically designed new bridge features artwork from local artists and pedestrian lanes offering beautiful views of Biloxi, Ocean Springs, and the Biloxi Bay.

The result is two aesthetically designed, long-lasting, and low-maintenance concrete bridges, which have replaced costly, high-maintenance bascule bridges. The new bridges also feature artwork from local artists. The new pedestrian lanes have become so popular with local residents that MDOT authorized a project to build a new parking area near the Bay St. Louis Bridge to make pedestrian access easier.

The new bridges are higher, wider, and longer than the structures they replaced. The record rebuild has helped reconnect communities, restore mobility, and renew the Gulf Coast infrastructure, economy, and culture. Communities on the Mississippi Gulf Coast are now stronger, and their futures are brighter.

Innovative Solutions for Local System Bridges

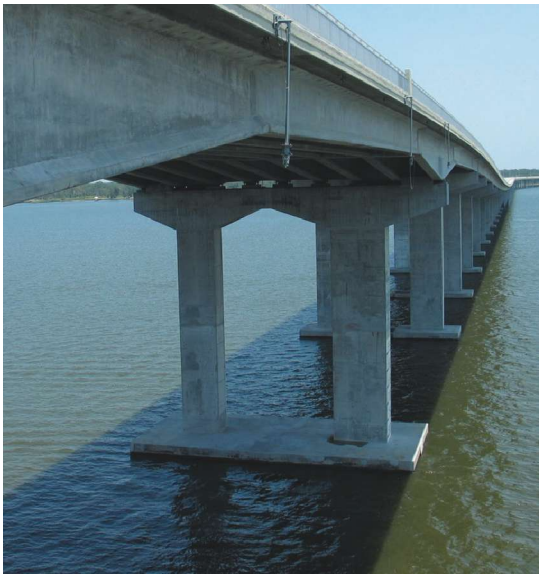
The City of Jackson closed a local bridge, located on Robinson Road between Raymond Road and the McDowell Road Extension, after a routine inspection indicated significant scour on the southeast corner of the bridge. After the closure on February 17, 2016, the scour caused the collapse of the end span on the three-span channel-beam bridge in March 2016.

Mississippi's local system traditionally uses 19-ft- to 31-ft-long reinforced concrete channel beams, but the City of Jackson was forced to search for an alternative solution to replace the bridge when this solution would not meet the following challenges:

- Existing utilities could not be moved.
- The existing roadway grade could not be raised.

The bridge was closed for nearly a year while city officials, the Federal Highway Administration, and MDOT's Local Public Agency (LPA) Division acquired funding and developed plans. Volkert was selected to design the replacement bridge.

With assistance from the local prestressed concrete industry, a design was developed for a bridge comprised of four FIBs that span 95 ft to address the needs of this project. The deck is CIP, and the abutments are CIP caps supported by concrete piles. The cap and piling were specifically designed and located to avoid



The new Bay St. Louis Bridge constructed after Hurricane Katrina is a fixed-span, high-rise bridge comprised of prestressed concrete bulb-tee girders with a multispan, haunched, post-tensioned concrete main span unit. The bridge connects Bay St. Louis with Pass Christian on the heavily traveled U.S. Highway 90 corridor along Mississippi's Gulf Coast.

existing utilities. The new bridge was opened to traffic on September 1, 2017.

This LPA project was the first use of FIBs in Mississippi. Having used this new feature on a small-scale project, MDOT is now planning to use these beams in multiple projects currently under design. MDOT will begin construction of Mississippi's first state-owned project using FIBs in the spring of 2018.

Aesthetic Bridge Solutions

With a robust concrete industry, MDOT is able to add aesthetic elements to bridges at a lower cost than would be possible with other construction materials. The U.S. Highway 61/84 Bridge over Liberty Road in Natchez, Miss., is a prime example of such a structure.

Liberty Road provides access to the starting point of the Natchez Trace Parkway at milepost 0. The Natchez Trace Parkway is part of the U.S. National Park Service and extends 444 miles from Natchez to Nashville, Tenn. It follows the Old Natchez Trace, a historic trail used by Native Americans, settlers, traders, and soldiers.

Also known as the Gateway to the Natchez Trace, the bridge over Liberty Road serves as the entrance to this national landmark. For this reason, its design needed to be signature in nature and invoke the feeling of entering the past. The bridge is a traditional two-span AASHTO Type IV girder bridge with a CIP deck, CIP abutments, and intermediate bents.

Aesthetic precast concrete panels and castings were added to the bridge to provide an attractive landmark. The castings and panels were cast by Jackson Precast, Jackson, Miss., a member of PCI Gulf South and a facility specializing in aesthetic panels and castings.

Preservation and Accelerated Projects

Concrete elements, both precast and CIP concrete, have provided Mississippi with low-cost, sustainable bridges constructed and maintained to be durable and dependable over the long term. With the flexibility of the federal Moving Ahead for Progress in the 21st Century Act (MAP-21), MDOT spends, on average, $100 million on bridge replacements, $3 million on preservation, and $20 million on rehabilitation annually. Prior to MAP-21, MDOT was only able to spend funds on replacements, leaving bridges to fall into disrepair. However, because of concrete's ability to withstand decay, MDOT's structures have fared well.

MDOT is eliminating joints on CIP decks by the use of link slabs and repairing open joints with modular and preformed joints.

In the past 15 years, MDOT has started to experience concrete deck deterioration in portions of north Mississippi bridges. Some of this deterioration has been linked to high chloride concentrations in concrete decks. In response to this problem and as part of the rehabilitation program, MDOT has developed a hydro-demolition and concrete-overlay process to repair these damaged bridge decks.

Since 1987, Mississippi's transportation funding has remained flat, while construction and maintenance costs have risen by more than 300%. MDOT has recently shifted its primary focus to system preservation, but it is still unable to keep up with infrastructure needs at the current funding level.

Accelerated bridge construction projects are becoming commonplace in MDOT's priority and project development. In the past, bridge replacement projects have required either new bridge construction to take place along a new alignment or for temporary detour roads and bridges to be constructed. The right-of-way and utility issues associated with these options make them both costly and time-consuming.

Moving forward, MDOT will perform more in-place bridge replacements, which will require road closures. Precast concrete systems allow for fast construction, reduce right-of-way and utility costs, and significantly reduce closure times and the impact on the traveling public.

In 2016, MDOT celebrated its centennial year by looking back at the great advancements and investments in the state's transportation network. Looking ahead, in the midst of funding challenges, MDOT will continue finding innovative solutions to sustain Mississippi's transportation infrastructure and future economic growth throughout the state.

Justin Walker is the state bridge engineer, Scott Westerfield is the assistant state bridge engineer, and Michael Flood is the public information officer for the Mississippi Department of Transportation in Jackson, Miss.

The U.S. Highway 61/84 Bridge over Liberty Road in Natchez, Miss., presents examples of precast concrete aesthetic panels and castings that the Mississippi Department of Transporation is able to add to bridges at a lower cost with a robust concrete industry in Mississippi.

CONCRETE CONNECTIONS

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

IN THIS ISSUE

http://www.i91brattleborobridge.com/construction_gallery.html
This is a link to a website presenting construction photos of the Interstate 91 Brattleboro Bridge. This bridge is the subject of a Project article on page 22.

http://nflroads.com/_layouts/FDOT%20D2%20Northeast%20Florida%20Road%20Construction/ProjectDetails.aspx?pid=268&sid=All
This is a link to the Florida Department of Transportation website that has information on the J. Turner Butler Boulevard (Interstate 95/State Road 202) interchange. Structures of this interchange are featured in articles on page 26 and page 34.

http://semaconstruction.com/project/i-95-j-t-butler-boulevard-designbuild
This is a link to a contractor's website that shows an aerial view of the J. Turner Butler Boulevard project. The Interstate 95/State Road 202 structure is the subject of a Project article on page 26 and a Concrete Bridge Technology article on page 34.

http://www.unionstation.org/westernexpansion
This is a link to a photo gallery of the recent western expansion of Union Station Kansas City. A part of the expansion project is a pedestrian and vehicle bridge that is featured in a Project article on page 30.

http://oregonjta.org/region2/?p=highway99w
This is a link to an Oregon Department of Transportation website that has photos, videos, maps, and a detailed project history of the Newberg Dundee Bypass. Bridges on the bypass are the subjects of two articles—a Project article on the Wynooski Road Bridge on page 14 and a Creative Concrete Construction feature on page 50.

https://www.youtube.com/watch?v=XcndEMU2izA
This is a link to a time-lapse video created from Mississippi Department of Transportation photos of the construction of the Biloxi Bay Bridge. Mississippi is the featured state in the article on page 52.

https://www.wsdot.wa.gov/publications/manuals/fulltext/M23-50/BDM.pdf
This is a link to the WSDOT *Bridge Design Manual*, which was listed as a reference in the Perspective article on page 10. See section 5.6.3 of the manual for information on lateral stability.

https://www.wsdot.wa.gov/publications/manuals/fulltext/M41-10/SS.pdf
This is a link to the WSDOT *Standard Specifications for Road, Bridge and Municipal Construction*, which was listed as a reference in the Perspective article on page 10. See Section 6-02.3(25) of the specifications for requirements related to lateral stability.

https://www.fhwa.dot.gov/bridge/concrete/nhi17071.pdf
Four comprehensive strut-and-tie modeling design examples are available on this link to the Federal Highway Administration (FHWA) website, as stated in the FHWA article on page 46.

https://www.concrete.org/store/productdetail.aspx?ItemID=CT16&Language=English
This is a link to ACI's Concrete Terminology (CT-16) document which was used for the Creative Concrete Construction article on page 48.

https://abc-utc.fiu.edu/mc-events/abc-rehabilitation-of-historic-franklin-avenue-bridge/?mc_id=229
This is a link to an archived webinar and PDF presentation, "ABC Rehabilitation of Historic Franklin Avenue Bridge," conducted by Accelerated Bridge Construction Center at Florida International University. This bridge is discussed in an article on page 38.

http://aspirebridge.com/magazine/2017Summer/Project-FranklinAvenueBridge.pdf
This is a link to "Franklin Avenue Bridge," an article that appeared in the Summer 2017 issue of *ASPIRE*® on the accelerated bridge construction methods for the restoration of the Franklin Avenue Bridge, which is also the subject of an article on page 38 of this issue.

OTHER INFORMATION

https://bookstore.transportation.org/collection_detail.aspx?ID=152
This is a link to purchase the recently published *AASHTO LRFD Bridge Design Specifications,* 8th edition.

https://abc-utc.fiu.edu
This is a link to the website for the Accelerated Bridge Construction University Transportation Center at Florida International University. Through this website, the user can register for monthly webinars on topics of accelerated bridge construction and access archived webinars.

http://www.wsdot.wa.gov/eesc/bridge/software/index.cfm?fuseaction=software_detail&software_id=69
This is a link to BridgeLink™, the Washington State Department of Transportation's (WSDOT's) software for prestressed concrete girder design that was mentioned in the Perspective article on page 10. It includes PGSuper, PGSplice, and PGStable software tools.

AASHTO LRFD Bridge Design Specifications: Stress Calculations and Prestress Loss Estimates

by Dr. Oguzhan Bayrak, University of Texas at Austin

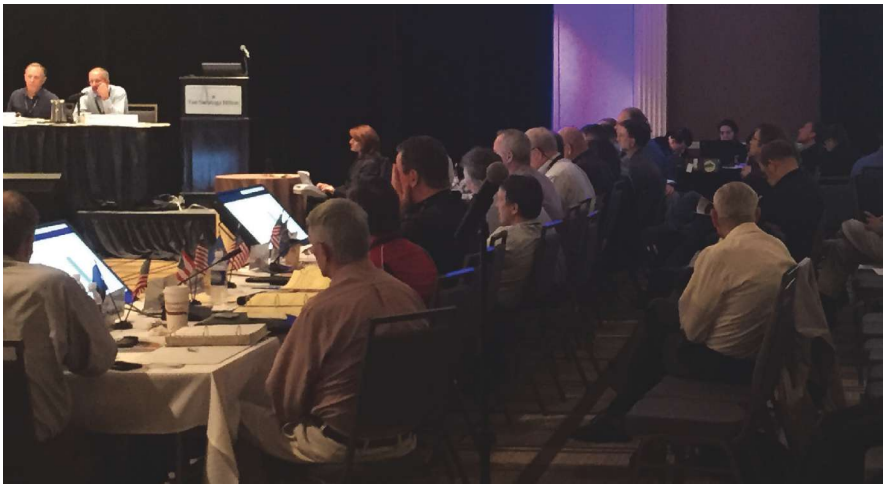
Since the last issue of *ASPIRE*®, a number of questions were raised about stress calculations under service loads for prestressed concrete bridges. This article reviews this topic and shares my thoughts.

The results from a survey of 38 state departments of transportation and from a sensitivity analysis by Brice et al.[1] were published in the Winter 2013 issue of *ASPIRE*. One of the primary conclusions of that article was that "*reducing the allowable tension stress at the service III limit state has the greatest overall influence and has the greatest impact on girder spacing requirements*."

In the same article, the authors noted that different states have different design policies and those policies that promote zero tension design result in more robust bridge designs than designs following the minimum requirements set forth by American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[2] It is always possible, if not recommended, to go beyond the minimum required by the AASHTO LRFD specifications; prestress loss estimations or stress calculations are not exempt from this reasoning.

Another aspect of the questions recently fielded by the *ASPIRE* team relates to what type of section properties (gross or transformed) are more appropriate for computing stresses for the Service III limit state when using the eighth edition of AASHTO LRFD specifications. To the best of my knowledge, there are no restrictions imposed by the specifications in this regard, and further lack of such limitations is consistent with the calibration efforts (that is, code calibration for service level stresses) that took place under Strategic Highway Research Program. In other words, one can choose to use any level of precision in calculating stresses, and the important aspect of this exercise relates to ensuring compliance with a particular state's design policy. Some states may choose a more conservative approach in this regard, while ensuring compliance with AASHTO LRFD specifications.

In an effort to shed additional light on the ongoing discussion on stress calculations, loss estimations, and the use of net, gross, or transformed section properties, let us consider the results of an example problem that I routinely use in my prestressed concrete design class at the University of Texas. As can be seen in the figure below, from left to right, there are increasing levels of analysis complexity.



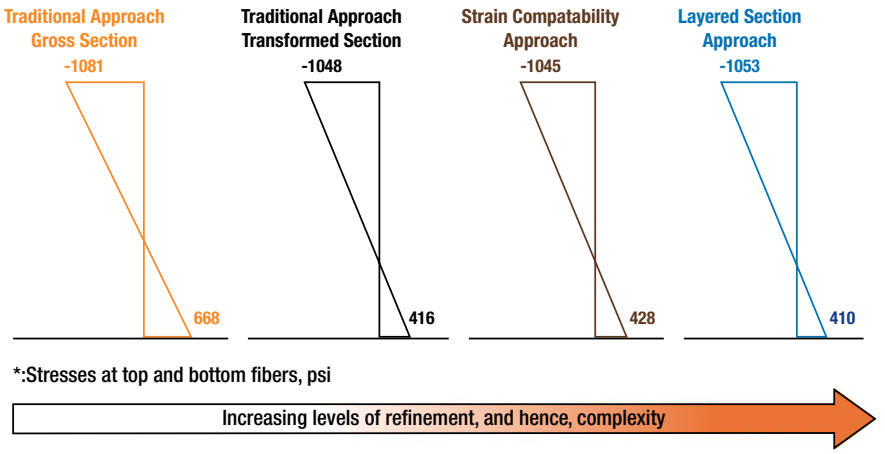
Voting on an agenda item during the 2015 SCOBS meeting. Photo: Dr. Oguzhan Bayrak.

Use of transformed section properties, or other higher-level analyses, such as strain compatibility analysis or layered section analysis, reduce the magnitude of the bottom fiber tensile stress by nearly 40% for this particular example in which a tee-shaped section that is similar to a decked bub-tee was employed. Certainly, higher-order analyses yield more accurate results and their use is recommended in computer-aided calculations.

With that stated, if a particular state's design policy calls for using gross section properties to build additional design conservatism in the calculations or requires zero tension, we must also understand, and respect that line of thinking. Further, some designers may wish to avoid complicated stress calculations in light of many other uncertainties inherent in design. Such uncertainties include the inability to estimate modulus of elasticity of concrete accurately, inaccuracies stemming from live load distribution, just to name a couple.

Because we are discussing accuracy versus conservativeness, it is also appropriate to discuss the prestress loss estimations. Regardless of the analysis technique used (that is, for all techniques shown in the figure below), it is also necessary to estimate the prestress losses. A design must account for losses related to elastic shortening, creep, shrinkage, and relaxation.

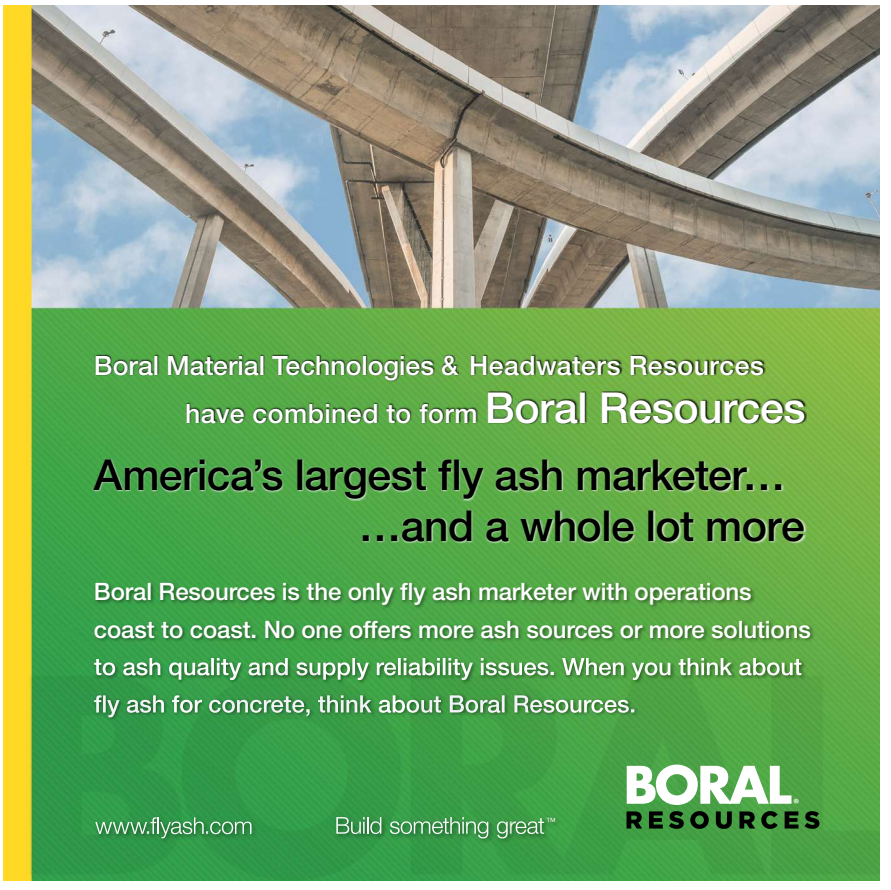
In running traditional calculations, with gross section properties as an example, we explicitly calculate all prestress loss components and account for them in our design. In higher-order analyses, the calculation of losses due to elastic shortening becomes implicit, and we therefore do not account for it explicitly. Losses due to creep can be accounted for by use of an effective modulus whereas shrinkage losses are typically calculated using a strain offset (or an explicitly calculated loss component) in design. Relaxation losses



The implications of refinement in analysis for bottom fiber stress calculations. Figure: Nathan Dickerson.

Table 1: Load Factors for Live Load for Service III Analyses (Adapted from Section 3 of *AASHTO LRFD Bridge Design Specifications*[2])

Component	Load Factor, γ_{LL}
Prestressed concrete components designed using the refined estimated of time-dependent losses in conjunction with taking advantage of transient elastic gains	1.0
All other prestressed concrete components	0.8



can also be tackled by using an effective modulus approach; it is typically a very small loss component for modern, low-relaxation strands. As an aside, it is important to note that the AASHTO LRFD specifications allow for the calculation of prestress "gains" due to transient loads; however, if such "gains" are calculated, stress checks in accordance with Section 3 of the AASHTO LRFD specifications is appropriate. In doing so, the stress "gains" experienced by the strands will be coupled with the precompression losses in the concrete that surrounds the strands. In this context, and to be clear about the requirements included in the AASHTO LRFD specifications, we must recall the revisions made to the specifications in the 2016 interim. The commentary provided for article 3.4.1 of the 2016 interim gives a clear explanation on when/where to use load factors of 0.8 and 1.0. For readers' convenience the table adapted from the specifications (Table 3.4.1-4 of the 2016 interim) is included in this article as the table above.

As discussed in this article, a designer can choose from several paths when running stress calculations. While all techniques are in compliance with AASHTO LRFD specifications, they may or may not be permitted by a particular state in new designs. For load-rating purposes, the benefits of a more refined analysis are clear, and, as we move forward, running such a refined analysis may help us better understand the actual bridge behavior.

References

1. Brice, Richard, Bijan Khaleghi, and Stephen J. Seguirant. 2013. "Evaluation of Common Design Policies for Precast, Prestressed Concrete I-Girder Bridges." *ASPIRE* Winter 2013: 10-11.
2. AASHTO (American Association of State Highway and Transportation Officials). 2017. *AASHTO LRFD Bridge Design Specifications*. 8th ed. Washington, DC: AASHTO (and earlier editions as appropriately referenced within the article).
3. Wassef, W.G., J.M. Kulicki, H.H.Nassif, A.S. Nowak and D.R. Mertz 2014. *Calibration of LRFD Concrete Bridge Design Specifications for Serviceability*, report on NCHRP 12-83 (in progress), Transportation Research Board, National Research Council, Washington, DC.

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