ASPIRE®

THE CONCRETE BRIDGE MAGAZINE

FALL 2021

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Bridge and Transit Firms Combine as International Powerhouse

SYSTRA-IBT carries on as a leader in transportation systems

NEW LONG X BRIDGE MERGES HISTORY WITH MODERN DESIGN
U.S. Highway 85, North Dakota

ATKINSON BOULEVARD OVER CSXT RAILROAD AND INTERSTATE 64
Newport News, Virginia

RAPIDLY RESTORING A VITAL TRANSPORTATION ROUTE IN NEBRASKA
Boyd and Holt Counties, Nebraska

Presorted Standard
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Lebanon Junction, KY
Permit No. 567

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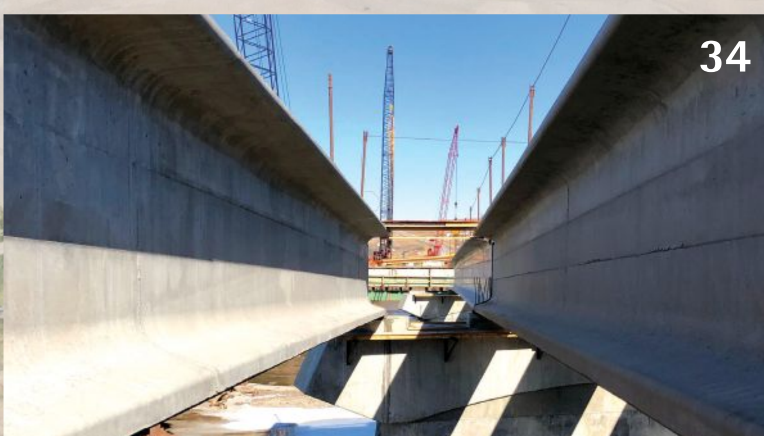

Photo: Olsson.

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Photo: PCI.

Old-School Practices, Innovation, and QA/QC Are All Critical to Success

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

Like many of you, I've finally had a chance to return to work in a more "normal" environment—how long that will last is apparently an unknown…

As you all know, I'm all about innovation, but you can also tell just by looking at me that I'm a seasoned engineer (I've had gray hair since I was 35) who's all about doing things right, double-checking the calcs and plans, and ensuring that our facilities support the traveling public and, above all, are safe.

Innovation moves our technology forward—we all want advances that deliver stronger, sustainable, durable, and attainable assets. But in his Professor's Perspective on page 40 of the Summer 2021 issue of *ASPIRE*®, "The Role of Analytical Tools in Innovation," Dr. John Stanton reflected that old-school techniques and practices can validate innovative ideas and concepts, and sometimes advanced programming and modeling breathe life into ideas not yet realized. His article is a great read for all engineering professionals, and I'd recommend it as a great primer for your engineer onboarding process.

Digital platforms and programs provide the calculating speed and modeling capabilities that influence our design solutions now and evermore, but there's still very much a place for old-school methodology in today's engineering. The tried-and-true systems of checking plans, calculations, and even new structural theorems are the bases for engineering assessments and quality control processes that digital programs don't necessarily take into account and, I'd argue, might bypass.

State-of-the-art computing and engineering require state-of-the-art quality programs. Craig Finley's Perspective on page 63 of this issue provides insight into the Finley Engineering Group's quality assurance/quality control (QA/QC) program deep dive. The decision to hit the pause button and look within is difficult when the pace of delivery directly conflicts with that choice, but in an effort to ensure that his company meets customer requirements while staying true to its standards of excellence, Finley did just that. He ordered an internal review and brought his QA/QC programs into the 21st century.

An academic or conceptual environment provides a space to test the boundaries of innovative ideas or "pie in the sky" concepts. It's truly the best place to allow creative ideas to grow, develop, succeed, or fail. Nobody gets hurt in a laboratory, and you've got your senior year or your master's or doctoral program to further an unproven concept before practitioners debate the deployment. Testing materials and structural systems during development and daily production can be challenging—testing is both art and science. In our profession, we live for the opportunity to test components beyond design capacity, chart failure, and apply the results to advance and strengthen analytical design models. Failure in the lab makes us stronger, but consistency in measuring is essential for the lab specimen and at the built bridge.

Back to analog versus digital. There is a place for both in today's testing world, and we must consider both to bring the best and safest product to the field. Our tried-and-true, consistent methods of testing are still very much valid. As we approach new testing concepts, we must demand the same procedural consistency as we expected in our previous testing. If laboratory environments aren't using evidence-based practices, results won't be consistent, and the lack of standardization may slow advancement, innovation, and implementation.

We're not the only industry that demands standardization in testing and in practical deployment, but at times we act like we are. Our challenge is to continue to seek new methods, practices, and products that deliver sustainable, efficient, and reliable systems without compromising the "old-school" methods that make us responsible engineers who deliver reliable and safe assets for the folks who use them.

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In partnership with Parsons, SYSTRA-IBT designed a 5-mile precast concrete segmental elevated guideway for a new light-rail system now under construction for the Honolulu Authority for Rapid Transit.

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

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CONCRETE CALENDAR FOR 2021–2022

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

October 5–8, 2021
PTI Committee Days
Hyatt Regency Coconut Point
Bonita Springs, Fla.

October 17–21, 2021
Virtual ACI Fall 2021 Convention
Online

November 8–10, 2021
ASBI 2021 Annual Convention and Committee Meetings
Westin La Paloma Resort and Spa
Tucson, Ariz.

November 15–21, 2021
PTI Certification Training: All Levels
Sheraton Austin Hotel at the Capitol
Austin, Tex.

December 8–10, 2021
Virtual Accelerated Bridge Construction Conference with Emphasis on International Experiences
Online

January 9–13, 2022
Transportation Research Board 101st Annual Meeting
Walter E. Washington Convention Center
Washington, D.C.

January 19–21, 2022
World of Concrete
Las Vegas Convention Center
Las Vegas, Nev.

March 1–5, 2022
PCI Convention with The Precast Show and National Bridge Conference
Kansas City Convention Center
Kansas City, Mo.

March 13–19, 2022
PTI Certification Training: All Levels
Doubletree DFW Airport North
Irving, Tex.

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

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

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

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

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

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

August 28–31, 2022
AREMA Annual Conference & Expo
Colorado Convention Center
Denver, Colo.

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

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

October 18, 2022
Call for Papers
The International Bridge Conference
Pittsburgh, Pa.

Correction

The Editor's Note that accompanied "The Digital Twin Evolution" Perspective in the Summer 2021 issue of *ASPIRE*® (page 17) incorrectly identified the example that David Parker used in his presentation at the Transportation Research Board to highlight the potential benefits of digital twinning. It should have referred to the March 2018 collapse of the Florida International University pedestrian bridge. *ASPIRE* regrets the error.

CONCRETE CRAFTSMANSHIP
Hamilton Form's Eye on Engineering

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Hamilton Form has long been recognized for high quality, custom engineered forms built to exacting dimensions. The FM 457 Bridge Replacement Project highlights our commitment toward innovation and finesse in forms to deliver a successful project.

The focus of this project was the construction of a Dual Corkscrew Bridge to replace an obsolete swing bridge over the Gulf Intercoastal Waterway in Matagorda County, TX. Precast was supplied by Bexar Concrete Works, Inc in San Antonio, Texas. Hamilton Form designed and fabricated forms to produce Modified TX96 girders, haunch girders with end blocks, drop-in sections with end blocks, and the bent caps. Along with all the formwork, Bexar Concrete Works also looked to Hamilton Form for the required Modified TX96 embed plates, splice girder embed plates, and erection hanger assemblies.

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FOCUS

Bridge and Transit Firms Combine as International Powerhouse

An international presence and innovations in segmental bridge design enable SYSTRA-IBT to carry on as a leader in transportation systems

by Monica Schultes

After a decade of study, community meetings, public outreach, environmental clearance, and utility coordination, the Mosquito Road Bridge Replacement Project in El Dorado County, Calif., is scheduled to break ground in 2022. This rendering shows the replacement bridge approximately 400 ft above the river; the original structure, visible at the bottom of the photo, will be retained for bicycles and pedestrians. Rendering: SYSTRA-IBT Viz Team.

In 2017, the world-renowned bridge-design firm International Bridge Technologies (IBT) joined the SYSTRA family. SYSTRA-IBT, as the wholly owned subsidiary is now called, is a top international bridge specialist. By joining forces with IBT, the SYSTRA Group extended its reach in North America, complementing existing bridge-design centers in France, South Korea, and India.

"SYSTRA at its core is a rail and transit company, but we have very strong bridge centers."

SYSTRA recognizes that bridges are a vital component of transportation infrastructure, their core business. "SYSTRA at its core is a rail and transit company, but we have very strong bridge centers," says Ben Soule, technical director of SYSTRA-IBT.

With more than 7000 employees located around the world, SYSTRA has grown through a combination of acquisitions and organic growth over the last decade. "Part of their global strategy was to bring IBT into the fold to enhance their bridge-design capabilities as well as their presence in North America," notes Soule. "Transit was a subspecialty of ours at IBT, so it was a good fit when we joined the SYSTRA family. There is a synergistic connection with our sister companies."

Shared Expertise

As a global organization, SYSTRA provides solutions via 350 dedicated bridge group specialists based in design centers in the United States, Canada, France, the United Arab Emirates, India, and South Korea. "The ability to trade expertise around the world and utilize all of the firm's specialties has provided us with more opportunities," explains Soule. When pursuing future work, it is especially beneficial to have technical proficiency and support, for example, with transit interfaces or subspecialties a bridge engineer might not be familiar with, such as power, signals, and stray

Phase 1 of the Chicago Transit Authority's Red-Purple Modernization project challenged design-build teams to develop concepts that could be constructed while service was maintained on portions of the existing 'L' train lines. The new precast concrete segmental box-girder solution reduced costs and offered a compressed schedule. Renderings: SYSTRA-IBT Viz Team.

Precast concrete segments for the Red-Purple Modernization project in Chicago, Ill. Although this is the first use of precast concrete segmental construction for the Chicago Transit Authority, the technology has been widely used around the world since Jean M. Muller, the famous French bridge designer and inventor, transformed segmental concrete bridge design. Several bridge engineers at International Bridge Technologies worked directly with Muller. Photo: SYSTRA-IBT.

current. "That is when the shared expertise has been really helpful," Soule adds.

Full Service

SYSTRA is known for offering a complete array of project services from concept to completion. That has its pluses and minuses, according to Soule. "The downside is that you have a short resume—you might be involved in just one project for years, from planning through commissioning," he says. "The upside is that we understand the nuances of every aspect of the project life cycle. You become a better consultant because you understand what is valuable to your client, whether it is an agency or contractor, and you can anticipate their needs."

The use of bridge information modeling (BrIM) helps SYSTRA-IBT integrate all facets of a project. "In the United States, we are still signing and sealing paper drawings as official documents, and 3-D [three-dimensional] models are not always part of the bidding process," says Soule. "However, the industry is moving toward digital delivery systems. We see it more often overseas, where other countries are ahead of us in that respect. SYSTRA colleagues working on the high-speed rail line in Great Britain are delivering final documents entirely as a digital model."

"Right now, BrIM is a great tool to generate 2-D plans, and we can see how it can lend itself to asset management for our clients," says Soule. "We were reluctant to embrace digital models as official construction deliverables, but the interface-heavy Chicago 'L' project has made us converts," he adds.

Using their experience in transit and segmental guideways, the design team of SYSTRA-IBT, SNC-Lavalin, and AECOM is adding more than 13 miles of new, fully automated and electric light rail to the Réseau express métropolitain transit system in Montreal, Quebec. The 4550 precast concrete segments, some weighing up to 58 tons, are being assembled by two launching gantries. Photo: *Réseau express métropolitain*.

Chicago's "L" Train

The Chicago Transit Authority (CTA) Red-Purple Modernization project includes a precast concrete segmental superstructure along an elevated section of the Chicago rail transit system. Working with lead design consultant Stantec, SYSTRA-IBT is responsible for both bridge design and the electrical grounding and stray current protection system for the segmental superstructure. The design-build joint venture of Walsh Construction and Fluor Corporation are currently constructing the project located in a congested part of Chicago. The segmental concrete solution was selected where practical for its construction efficiencies, and it reduced total cost of ownership over a traditional steel design, for which the CTA is well known.

Soule commented, "Our team developed an alternative technical concept, then communicated the advantages to CTA. This project demonstrated the benefits of BrIM for communicating information quickly and efficiently, and ultimately for CTA asset management."

Design-Build Project Delivery

"I would estimate that 80% to 90% of our projects are design-build, which plays into the SYSTRA-IBT experience very well," says Soule. The firm's vast experience lends itself to integrated project delivery methods. By considering life-cycle costs during each stage of design development, the company has achieved a reputation for identifying innovative designs that reduce operational costs.

By considering life-cycle costs during each stage of design development, the company has achieved a reputation for identifying innovative designs that reduce operational costs.

The now completed 1.91-mile-long Atlantic Bridge across the Panama Canal has a 1740 ft main span, which was built using the balanced-cantilever method with traveling forms. The concrete superstructure for the cable-stayed spans consists of longitudinal concrete boxes connected with transverse diaphragms. The deck is supported by two planes of stay cables anchored along the edges. During bridge construction, the Panama Canal could not be closed to shipping or used for construction access. Photo: VINCI Photo Library.

"The selection of teams based on qualifications instead of pure low bid is still evolving. On complex projects, designer-contractor collaboration is here to stay," says Soule.

Third Panama Canal Crossing

SYSTRA-IBT recently played a key part in designing the world's longest all-concrete cable-stayed main span bridge, which crosses the Panama Canal near the port city of Colón. The Atlantic Bridge was a design-bid-build project for the Panama Canal Authority, and SYSTRA-IBT was retained in an engineering role by the winning contractor, VINCI Construction. As the project progressed, the design was modified to improve constructability while retaining aesthetic features from the original design. This led to a reengineering of the entire structure to better align the structural elements with the preferred construction methods. SYSTRA-IBT led those design efforts for the main span in partnership with the engineering group from VINCI. The result is a concrete cable-stayed bridge with a main span of 1740 ft. The 26-ft-long segments were cast in place with a customized form traveler that could accommodate the complex deck cross section.

Mosquito Road Bridge

SYSTRA-IBT targets large, unconventional bridge projects such as cable-stayed,

Mentorship and Technical Contributions

SYSTRA-IBT's design philosophies and culture are deeply rooted in a mentor-apprentice tradition that continues to this day. Several bridge engineers at International Bridge Technologies (IBT) worked directly with the late Jean M. Muller, the famous French bridge designer and inventor who transformed segmental concrete bridge design. Muller is credited with the development of the match-casting technique widely used in modern precast concrete segmental construction. His design for the Brotonne Bridge in Normandy, France, with its 1050-ft main span, was the first example of a concrete box girder supported by a single plane of cable stays. He also invented the delta frame concept, a unique way to make long segmental cable-stayed bridges wider to accommodate more traffic lanes.

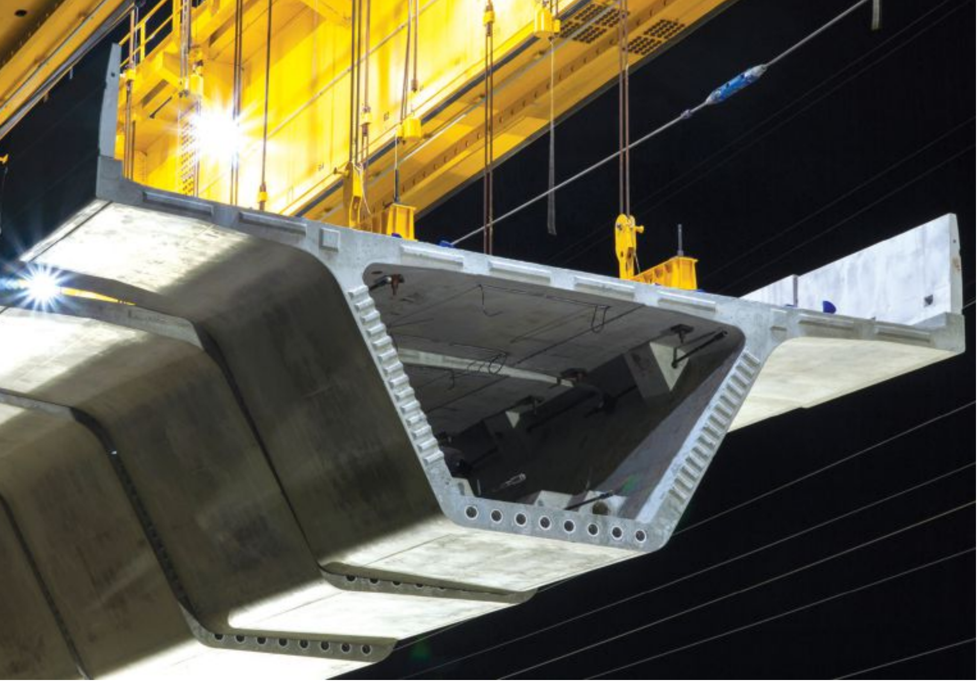
As a young engineer, IBT cofounder Daniel Tassin was sent to the Florida Keys to supervise construction of Muller's segmental designs, which included several other revolutionary ideas, such as external post-tensioning and span-by-span erection. These technologies are taken for granted in segmental design and construction today.

With these accomplishments and those carried out by Tassin and others he mentored, Muller left a rich legacy of technical achievement as well as elegant structures that are admired for both their lasting engineering excellence and their appealing aesthetics.

"Credit for our success goes to our mentors," says Mike Smart, SYSTRA-IBT president, who cofounded IBT in 2000. "Most of the precast [concrete] segmental concepts that we use in the U.S. were introduced by Muller decades ago. Although segmental construction is now common, it is still complex. Thankfully, we've had access to the Muller-Tassin answer key all this time to help guide us through most of the same challenges that were faced when it was all considered 'unproven' technology."

Recently inducted into the National Academy of Engineering in recognition of his unique contributions to the profession, Tassin continues to mentor SYSTRA-IBT engineers. "We continue to learn from the winning bridge concepts that he envisions and sketches on sheets of paper," notes Smart.

Notably, several of SYSTRA's leading bridge engineers were also apprentices of Muller, and Muller himself worked for the legendary engineer Eugène Freyssinet, who is considered the inventor of modern prestressed concrete. Given this mentoring pedigree, it is no wonder that SYSTRA-IBT is synonymous with attractive, efficient concrete structures.



A 5.2-mile-long precast concrete segmental elevated guideway in Honolulu, Hawaii, is currently under construction. The structure, designed by Parsons and SYSTRA-IBT, is the third in a series of projects for the Honolulu Rail Transit Project, a 20-mile-long grade-separated, fixed-guideway transit system. Photo: SYSTRA-IBT.

launched, transit, and segmental bridges. "We look for those particular projects wherever they may be. But the larger, more complex projects are of particular interest to us," says Soule.

"The larger, more complex projects are of particular interest to us."

A recent example is the Mosquito Road Bridge spanning the South Fork of the American River in El Dorado County, Calif. The three-span, post-tensioned concrete box-girder bridge has a 536 ft main span with 322 ft end spans. Starting in 2022, the segmental concrete bridge will be constructed using the cast-in-place balanced-cantilever method. Working with design partner Quincy Engineering for the El Dorado County Transportation Division, SYSTRA-IBT is responsible for detailed design calculations and drawings of the superstructure as well as review of the foundation design.

Bridging Challenges

While SYSTRA-IBT has been fortunate with acquiring and retaining talent, finding bridges to design has been a challenge recently. "Over the last five years, there has been a dearth of funding in the United States. Most large bridge projects require federal dollars, so we are optimistic about the transportation bill gaining momentum in Washington. Also, while it hasn't reached us yet, we will certainly feel the effects of material price increases and labor shortages in construction. More than anything else, the challenge will be getting these projects off the ground," predicts Soule.

Transit has not been a priority in the United States, other than in a few major metropolitan areas. This trend may be changing. but transit design is still challenging. Much of the United States has aging infrastructure, which often limits design options. This is where segmental technology often makes sense.

Light-Rail Upgrades

A current example of segmental technology is underway in Honolulu, Hawaii. In partnership with Parsons, SYSTRA-IBT recently designed a 5-mile elevated guideway for a new light-rail system for the Honolulu Authority for Rapid Transit (HART). Designed for the high-seismic area, the substructure consists of single reinforced concrete piers on monoshaft supports. The precast concrete segmental superstructure is being erected span by span with a self-launching overhead gantry. The airport segment will be the third section of the route to be completed; it is currently being constructed by a joint venture of Shimmick/Traylor/Granite.

In several other countries, transit is a much greater infrastructure priority, as public transportation is part of everyday life and supports a substantial user base that is often lacking in many U.S. cities. For example, in Montreal, Quebec, a new public transit project, Réseau express métropolitain, is underway for the Caisse de dépôt et placement du Québec (Quebec Deposit and Investment Fund). Working with design partners SNC-Lavalin and AECOM, SYSTRA-IBT is responsible for design of the elevated-guideway structure for a portion of the new, fully automated electric light-rail network. The precast concrete segmental guideway, which includes 4550 precast concrete segments assembled by two launching gantries, is currently under construction by NouvLR, a consortium that includes SNC-Lavalin Grands Projets, Dragados, Pomerleau, EBC, and Groupe Aecon Québec Ltée.

High-Speed Solutions

In addition to its light-rail experience, SYSTRA-IBT is a world leader in the design of high-speed elevated guideways. Though such guideways are not currently found in the United States, the need is there, and this trend may be changing, too. The California High-Speed Rail project continues, despite several cost, schedule, and funding challenges. Another high-speed rail route between Dallas and Houston was initiated recently in Texas, and several other high-speed rail routes have been envisioned by the U.S. Department of Transportation Federal Railroad Administration as part of its High-Speed Intercity Passenger Rail Program. Still, the United States lags far behind Europe and Asia in high-speed rail development. "The U.S. won't generate any excitement until there are riders," says Soule. "Once we see some benefits and move people quickly, it will happen in other areas of the country," he predicts.

With decades of transportation experience, SYSTRA-IBT successfully tailors solutions to specific client needs and local stakeholders. The company seeks out complex and challenging projects to solidify their role as the go-to engineering consultants for transportation system design and development.

Advancing Bridge Inspection and Asset Management Through Digital Twin Technology

by Monica Schultes

Digital twin technology shows huge promise for supplementing bridge inspection practices and monitoring the health of structures. A previous article (see the Summer 2021 issue of *ASPIRE*®) introduced the concept of a digital twin and explored how the technology might impact the bridge design and construction industry. This article focuses on using the new technology for bridge inspections and asset management.

Bridge Inspection Tools

Traditional hands-on visual inspections are labor intensive, require expensive equipment, present safety risks, and can be error prone. Agencies such as the Minnesota Department of Transportation (MnDOT) are turning to unmanned aerial vehicles (UAVs), also known as drones, to overcome such challenges.

"The Stone Arch Bridge in Minneapolis is a good example of how we have used UAVs for bridge inspection," says Kevin Western, state bridge engineer for MnDOT. "With the model developed from UAV footage, we can clearly identify cracks and missing mortar, and identify where repairs are needed. That helps the design team develop construction plans and allows us to easily communicate to the contractor," he adds.

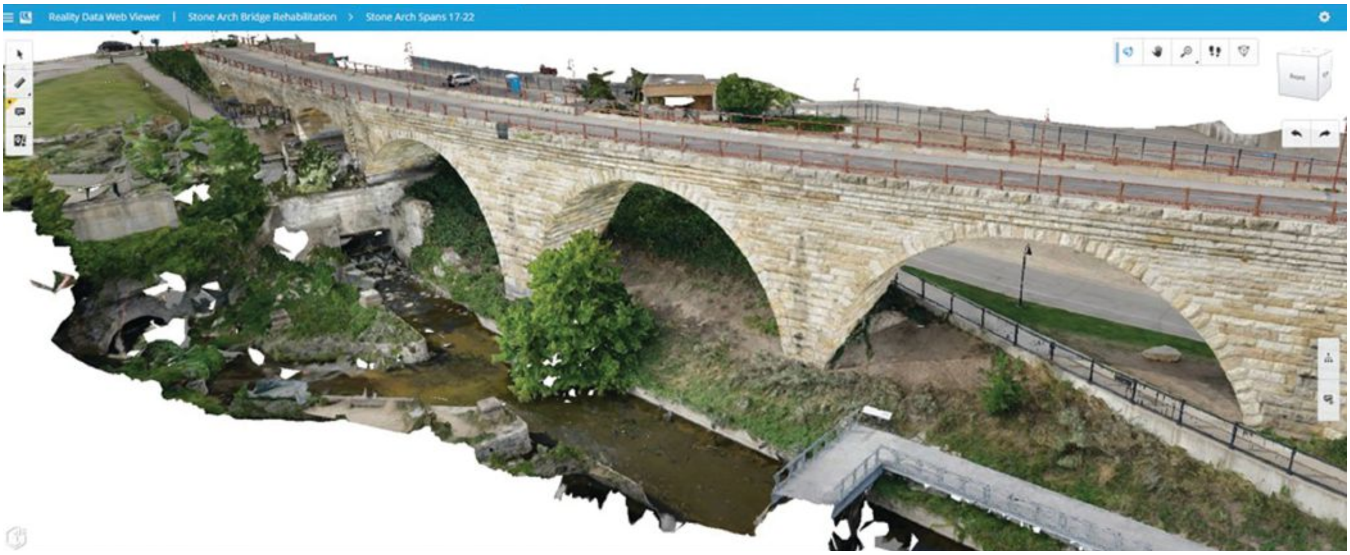
With a grant from the Federal Highway Administration, MnDOT obtained drones for each of its eight districts. The agency is in the process of training employees how to use the UAVs to assist in inspections and provide information for inventory reports. MnDOT is still defining best practices to take that information and communicate it to evaluation and design teams.

According to Western, "Drones are a tool. We still use snooper trucks and other methods, but the drones allow us to inspect areas of the bridge safely and cost effectively."

"Drones are a tool. We still use snooper trucks and other methods, but the drones allow us to inspect areas of the bridge safely and cost effectively."

Simply taking drone footage is not enough. For example, an inspector failed to discover a crack in an Interstate 40 structure over the Mississippi River that prompted the span's closure. Western

The Minnesota Department of Transportation used unmanned aerial vehicles (drones) to capture photos, videos, and other data to produce a high-resolution "reality mesh" of the Stone Arch Bridge, as shown in this screenshot. These collected data are used to create a digital twin representation that can assist with inspection of the bridge, and the reality mesh can provide insights into structural changes over time. Photo: Minnesota Department of Transportation.



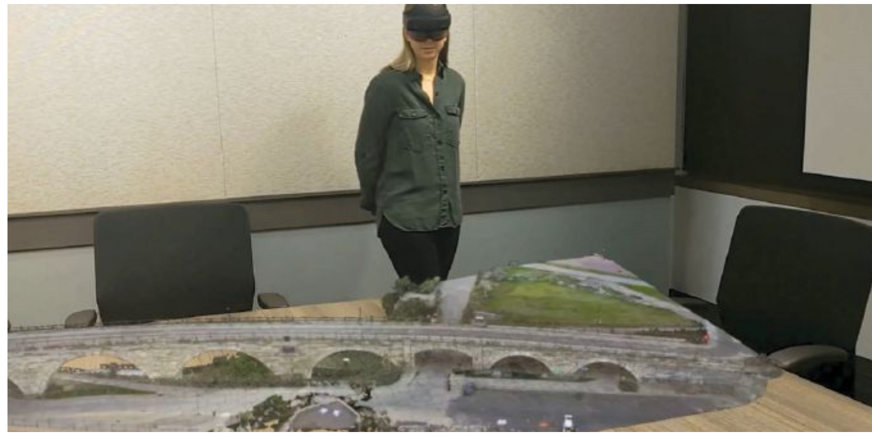
explains, "The footage was there, but no one was looking for or expecting a crack. We have to understand how to incorporate drone footage into the inspection process even before we start collecting and evaluating it."

Holistic View

While drones play an important role in capturing data, they are just one tool in the arsenal of an agency working to build and maintain digital twins. Another important tool is the right software. "Bentley Systems software combines data from surveys, photogrammetry, LiDAR [light detection and ranging], and sensors, as well as drone footage in the digital twin database," says Dan Vogen, vice president of road and rail asset management at Bentley Systems.

Because bridges have such a long life cycle (typically 75 to 100 years), it is important to track changes to the structures over time. A holistic view of the bridge is achieved by layering information from past inspections on top of current data to better understand what is happening on site.

"This is a great opportunity for agencies to use UAVs to complement and augment in-field inspections. The modern method of inspecting bridges uses drones and photogrammetry," says Vogen.



The software company Bentley Systems is adopting Microsoft HoloLens technology so that bridge inspectors can immerse themselves in the full-scale digital model of the bridge they are inspecting. The use of augmented reality aims to improve the connection between the bridge information model and actual field conditions. Photo: Bentley Systems.

The data from these inspections can be reviewed quickly and easily in the office by viewing a time-lapse comparison of changes and noting areas of concern and anything that needs to be reviewed in the field. Also, field crews can see all the inspector's notes right on the structure's digital twin, which is more visual, more accurate, and more efficient. All of this is geared toward saving costs, avoiding risks, and reducing time required for inspections.

Bridge inspection methods have remained stagnant for many years. Accessing and assessing an entire structure can involve snooper trucks, boats, or rappelling over the side of the structure. But a snooper truck is limited compared with the capability of a drone in hard-to-reach places. "We can fly a drone up under the deck, along the beams, and get the picture," says Vogen.

Geometric Accuracy

A camera-equipped drone on a repeatable flight path can capture a more accurate picture than an on-site inspector, who might focus on some things to the exclusion of others. The model is generated from thousands of pictures. It is geometrically accurate, says Vogen. The Federal Aviation Administration (FAA) recently relaxed restrictions for drone flight, making drone-based bridge

Software can piece together photos taken by an unmanned aerial vehicle to create a visually accurate and detailed model of the entire bridge in a process using photogrammetry technology. Using the three-dimensional model created by the software, different views of the "reality mesh" of the Stone Arch Bridge project were generated by the Minnesota Department of Transportation. Photo: Bentley Systems.

Minnesota Department of Transportation (MnDOT) is one of many agencies employing drones as a way of innovating for a better outcome in its bridge inspection practices. MnDOT inspectors can conduct significant parts of the inspection while in the office. This reduces time in the field, making the overall inspection more efficient, safer, and more cost effective. Photo: Minnesota Department of Transportation.

inspection possible. "The FAA now allows the use of the drones without direct line of sight," explains Vogen. Meanwhile, the Federal Highway Administration currently allows the use of drone-based inspection as a supplement to, but not a substitute for, in-person inspections.

Bridge inspections have always been dangerous, but for many old-school engineers, nothing beats being there. Bentley is bridging the gap between staring at photos and being on site. The high-resolution drone photographs of the bridge are stitched into a "reality mesh" three-dimensional (3-D) model comprising hundreds of millions of polygons, explains Meg Davis, industry marketing director of road and bridge at Bentley Systems.

This mesh contains far more information than regular 3-D models, says Davis. "It has all the texture, all of the current conditions conveyed through the reality mesh."

The reality mesh can be viewed on a computer or tablet, or a cloud-connected HoloLens (augmented-reality headset) can be used to examine the bridge at a zoomed-out tabletop view or at a 1:1 scale; this lets engineers get up close and see every inch of the structure in high resolution. While this technology is not meant to replace in-person inspections, it has reduced the number of trips needed to inspect the bridge and has also allowed engineers to contribute from remote locations.

Looking Forward

MnDOT is already experiencing benefits in safety, tracking, and quality from drone bridge inspections, while also believing there will be long-term cost savings by using UAVs. "We are in the infancy of this technology. A bridge can last 75 to 100 years, so right now we are seeing only a snapshot over that lifetime," says Western.

MnDOT is also evaluating the use of sensors on bridges. "We have tried sensors on several projects and are still in the evaluation stage. There are challenges such as false positives and the longevity of the instrumentation, as well as understanding and interpreting the data," explains Western.

"How do we take the information and make better decisions going forward? That is the 'Holy Grail' for asset management. We are headed in the right direction here at MnDOT and are already seeing huge benefits. This increase in technology may ignite some excitement from young engineers and designers. Any way we can recruit young talent is a good thing," he says.

"How do we take the information and make better decisions going forward? That is the 'Holy Grail' for asset management."

A Different Perspective

Although digital twin technology shows great promise, there is still work to be done. Coming from a metrology (the science of measurement) perspective, David H. Parker, Parker Intellectual Property Enterprises LLC, challenges the industry to examine the instrumentation attached to structures. "Is the bridge industry gathering the right information?" he asks.

There are cases where we have relied on visual inspections to avoid disasters. But serendipity should not play a part in bridge monitoring. Digital twin technology is designed to remove some or all of this subjectivity.

"We shouldn't just throw sensors at a bridge and expect the data to illuminate what is happening in real life," says Parker. "I think there is a disconnect between bridge owners and researchers. The bottom line is determining if the bridge is safe. Engineers need to intuitively understand information flowing to them through the model and easily detect anomalies.

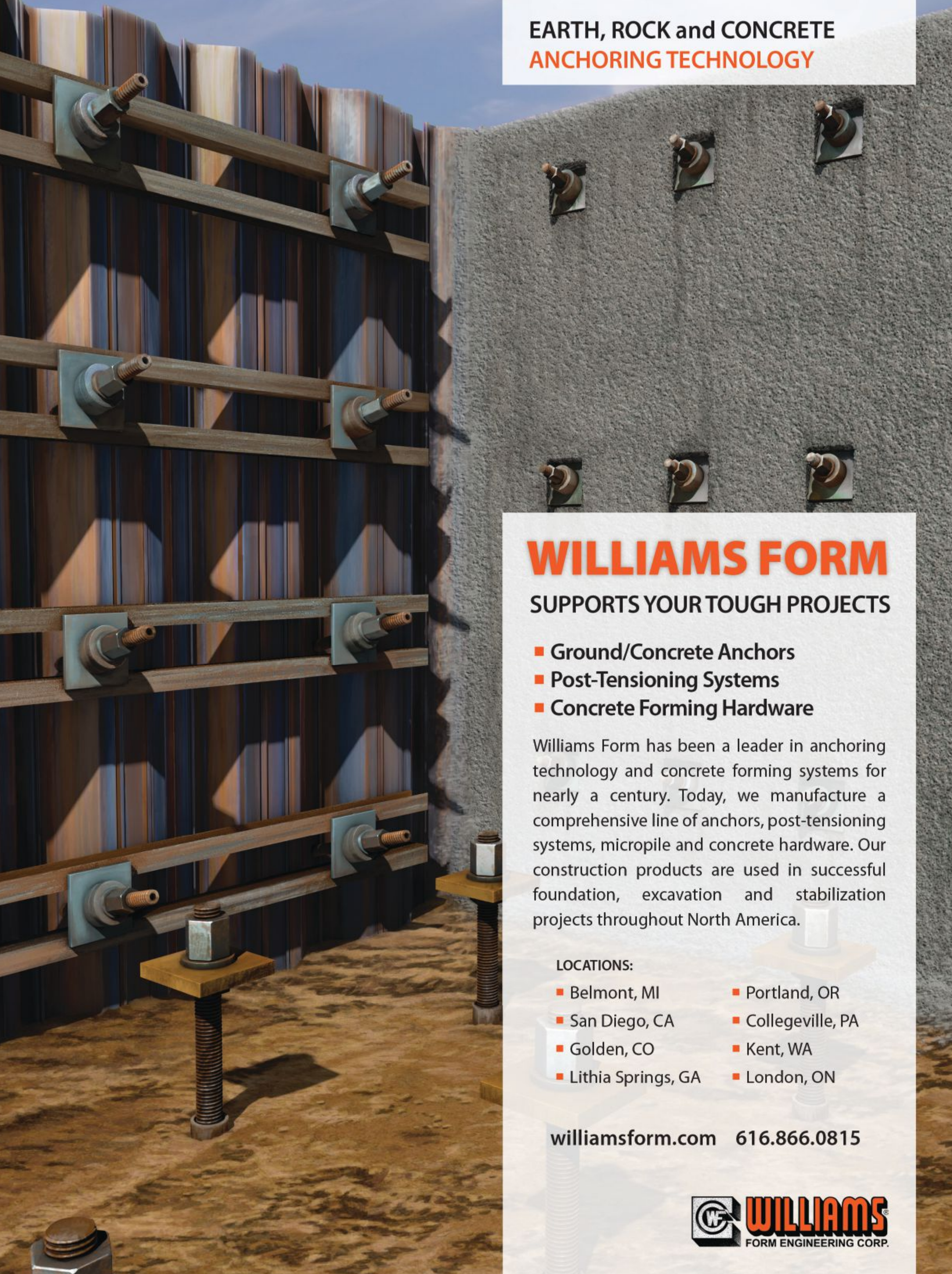
"We shouldn't just throw sensors at a bridge and expect the data to illuminate what is happening in real life."

"Does the bridge industry verify the actual movement of the bridge against their predictions? We need some degree of assurance that the model and the sensitivity of the data are correct."

In a follow-up article in the next issue of *ASPIRE*, Parker will expand on these topics and describe how to use high-accuracy dimensional metrology for monitoring structural health.

Conclusion

Just as office buildings use building management systems to regulate maintenance and operations, bridges are dynamic assets that demand close monitoring after they are built. Digital twins enable bridge owners to take advantage of the tremendous quantity of data obtained from remote inspections. This reduces time spent in the field, which makes the overall inspection quicker, safer, more efficient, and less costly. Bridge asset management based on visual inspections, which are subjective, time-consuming, expensive, prone to error, and sometimes dangerous, is changing for the better.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Design of Components or Systems?

by Dr. Andrzej S. Nowak, Auburn University, and Dr. Thomas Murphy, Modjeski and Masters

In the current American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*,[1] design is based on the consideration of individual structural components such as beams, columns, tension members, and connections. For each component, the specifications require that the load-carrying capacity exceed the design load, with the appropriate load and resistance factors applied. This concept is easy to understand, and it works well for simple structural systems such as simply supported girder bridges. The load per girder is calculated and compared with the calculated load-carrying capacity or resistance of the girder. In LRFD codes, the factors applied to loads and resistance are established using the statistical variability of load and resistance for a type of element to obtain an acceptable target reliability index. A reliability index is calculated using statistical parameters of load and resistance.

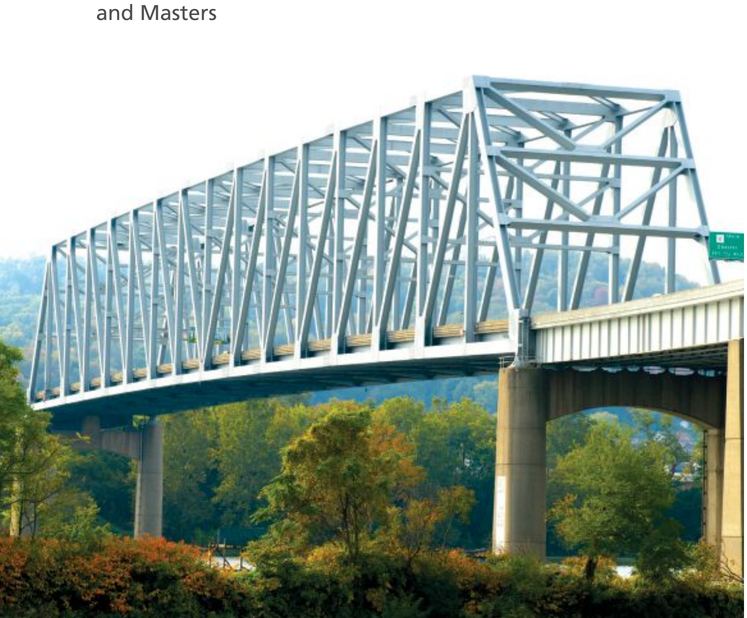
Bridges, however, are usually complex structures, and a design approach that only considers isolated elements may be overly conservative, especially for bridges such as single- or multiple-cell box girders, or even for slab bridges. Certain questions that seem straightforward for simply supported girder bridges can be difficult to answer for complex structures. Examples include, "What is the load for a bridge?" and "What is the structure's capacity or resistance?" To answer these questions more completely and accurately, the behavior of a bridge *as a system* must be considered. This article discusses the issues related to system-level versus component-level behavior and design.

Load and Resistance

For this discussion, it is assumed that the major load components are dead load and live load. The definition of live load for a girder in a multigirder bridge involves either applying truck and lane loads using girder distribution factors or a refined analysis to determine the distribution of live loads. The load is expressed in terms of a moment or shear force, or stress and strain. However, in practice, the definition of live load can be much more complex because the load is not necessarily a single truck—it can include multiple vehicles in different lanes and side by side. The effect of live load depends not only on the weight of the trucks but also on their transverse (distance from curb) and longitudinal position. The availability of an extensive weigh-in-motion (WIM) database provides a sufficient basis for the development of statistical parameters of live load for not only girders but also whole bridges.

Even more complex than the definition of bridge live load is the definition of bridge resistance, even on a component level. Girder resistance is defined as the moment-carrying capacity, shear capacity, or maximum allowable stress. The load-carrying capacity of a girder is generally well understood and can be evaluated analytically and confirmed by laboratory testing of components. Test results provide information about the statistical parameters of resistance

A statically determinate truss bridge is an example of a bridge than can be considered a series system, where failure of one element may result in failure of the system. All Photos: Modjeski and Masters



A multigirder bridge is an example of a bridge that behaves as a parallel system, where the load previously carried by a failed element can be distributed to other elements without causing system failure.

in typical girders designed according to the current specifications. However, girders do not exist in isolation; they are interconnected with other components through deck slabs and diaphragms or bracing. In structure types other than multigirder bridges, the interconnection between components can be even more complex. As the load increases and the system deforms, load is distributed to and shared by other components. The ability of a bridge to share load between components is strongly affected by ductility and redundancy. Therefore, prediction of the load-carrying capacity for the whole bridge requires consideration of multiple load paths, and the deformation behavior of all involved components into the nonlinear regime, typically requiring a three-dimensional (3-D) nonlinear analysis or perhaps proof-load testing.

Ductility and Redundancy

Ductility can be described as the ability of a structure or component to undergo considerable deformation before ultimate failure. The load-deformation (strain or deflection) relationship for a ductile component typically has a pronounced plateau where deformation increases with little or no additional load. An example of a ductile material is low-carbon steel, and an example of a ductile component is a reinforced concrete beam with a low reinforcement ratio.

Redundancy is the ability of a system of structural components to share the load through multiple load paths. When a structural component is overloaded and close to reaching its ultimate capacity, load is transferred to other components. Therefore, in a redundant structure, overloading of a single component does not typically result in failure.

Structural Systems

A useful way of thinking about structural systems is to classify them as series or parallel systems.

In a series system of elements, overloading/failure of any one element triggers a failure or collapse of the total system. An example of a series system is a chain, as its strength is determined by the strength of the weakest link. Statically determinate trusses are also series systems (when ignoring 3-D behavior).

A parallel system of ductile components has an ability to resist the load even after one or more elements reach their ultimate capacities. An example of a parallel system is a cable that consists of multiple wires, or a multigirder bridge with a reinforced concrete deck that helps distribute the live load from an overloaded girder to adjacent girders.

Most bridges are a combination of components or elements connected in series and in parallel, so an accurate system model can become very complicated. In addition, an important factor that affects the reliability of bridge systems is the degree of mutual relationship or connection between elements, which can be represented by a coefficient of correlation. In general, quantification of correlation is very difficult because of a lack of data. It can involve answering questions such as, "Are there considerable differences between components with regard to quality of materials and workmanship?" A high degree of correlation is helpful for series systems, but undesirable in parallel systems.

Code Calibration

The reliability-based calibration of design specifications involves the development of statistical parameters for load and resistance, development of a reliability analysis procedure, selection of the target reliability index, and derivation of load and resistance factors. However, the original calibration of the AASHTO LRFD specifications was performed for individual bridge components, and not for the system as a whole. In general, the reliability of the whole bridge is higher than the reliability of a single girder, but whether this is true in a specific case depends on the structural type, ductility, redundancy, and correlations.

Given improvements in analytical capabilities, system reliability-based calibration is now feasible. It would require the selection of a wider set of representative bridges, adoption of live-load models from the available WIM database, development of statistical parameters for system load and system resistance, development of an analytical procedure for modeling failure scenarios, selection of the system target reliability index, and, finally, derivation of load and resistance factors for the considered bridge systems.

However, there are issues to be considered when contemplating a shift to system calibration. When engineers speak of redundancy, they generally mean the ability of a structure to accommodate component damage or failure. Such accommodation typically requires a member loss analysis, which is not necessarily the same as a system calibration. System calibration involves consideration of the behavior of the bridge system under increasing loads and how those loads are redistributed as members approach their ultimate resistance, as well as consideration of system reliability procedures. When ductile behavior is assumed, an unintended consequence of using a system reliability design approach may be a reduction in required individual member resistance when compared with the component-level design approach. This difference can negatively affect the ability of a structure to accommodate unanticipated member damage or loss.

This effect is similar to the effect of using refined analysis rather than approximate methods during the design. The end result of a refined analysis is typically less required resistance in the constructed component due to less conservative analysis results, and the previously stated approach to the target reliability index. The Federal Highway Administration's *Manual for Refined Analysis in Bridge Design and Evaluation*[2] provides a more thorough discussion on this topic. To ensure that the intended outcome is achieved, consideration needs to be given to what the ultimate goals of a system calibration approach would be.

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Benefit-Cost Analysis: Showing the Value of Bridge Preservation

by Dave Juntunen, The Kercher Group, a Mott MacDonald company

As the nation once again debates a new national transportation bill, the condition of our highway bridges enters center stage. We all know that bridges are vital to our transportation networks, and we are challenged to manage them using the concepts of sound asset management. In Section 515.5 of Title 23, Highways, the Code of Federal Regulations (CFR)[1] defines asset management as follows:

> *A strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life cycle of the assets at minimum practicable cost.*

The Federal Highway Administration's (FHWA's) *Bridge Preservation Guide*[2] defines maintenance, preservation, rehabilitation, and replacement actions. **Figure 1** lists the National Bridge Inventory (NBI)[3] condition-rating ranges and the terms associated with them for main bridge components. Bridge replacement includes the total replacement of a bridge. Bridge rehabilitation involves major work required to restore the structural integrity of a bridge, including partial or complete deck replacement, superstructure replacement, or major substructure repairs or partial replacement. Replacement and rehabilitation actions are typically done to bridges in poor condition, and the result is a bridge in good or fair condition.

	NBI Rating Scale (from 0 – 9)	9 8 7 Good	6 5 Fair	4 3 2 1 0 Poor
Bridge	Deck (Item 58)	≥7	5 or 6	≤4
Bridge	Superstructure (Item 59)	≥ 7	5 or 6	≤ 4
Bridge	Substructure (Item 60)	≥ 7	5 or 6	≤ 4
	Culvert (Item 62)	≥ 7	5 or 6	≤ 4

Figure 1. National Bridge Inventory (NBI) condition-rating categories for main components. Figure: Dave Juntunen.

Preservation actions are cost-effective means of extending the service life of a bridge, typically keeping a good bridge in good condition, and a fair bridge in fair condition. There are many examples of bridge preservation actions, including deck overlay, deck expansion joint replacement, deck patching, structural steel cleaning and coating, and sealing concrete superstructures. (See the Spring 2021 issue of *ASPIRE*® for a Perspective article on two forthcoming guides on bridge preservation from the American Association of State Highway and Transportation Officials.)

Figure 2 shows the bridge action categories available for bridge asset management. So, what is the best combination of these actions over the life of a bridge? This can be answered using a bridge management system (BMS). The FHWA Minimum Standards for Developing a Bridge Management System[4] state that a BMS for National Highway System pavement and bridge assets shall include documented procedures for the following:

- Collecting, processing, storing, and updating inventory and condition data
- Forecasting deterioration
- Determining the benefit-cost over the life cycle of assets to evaluate alternative actions
- Identifying short- and long-term budget needs for managing the condition of bridge assets
- Determining the strategies for identifying potential projects that maximize overall program benefits within the financial constraints
- Recommending programs and implementation schedules to manage the condition of bridge assets within policy and budget constraints

At the heart of an advanced BMS is benefit-cost analysis, where all possible combinations of actions

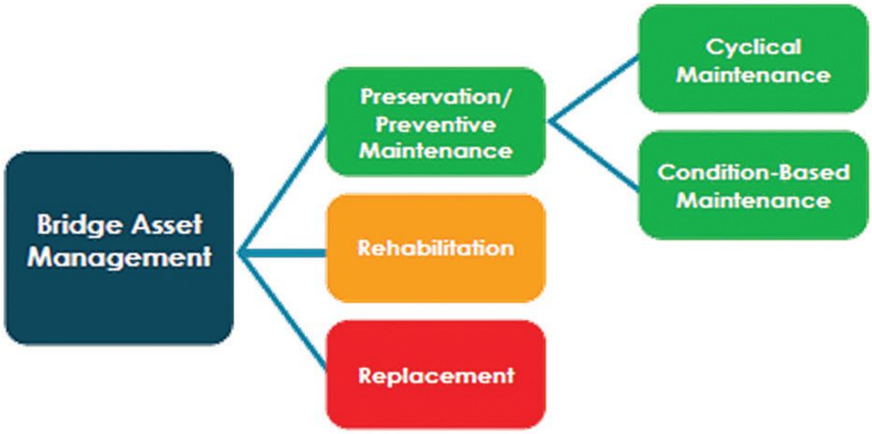

Figure 2. Effective bridge asset management includes a combination of the different types of bridge action categories. Source: Federal Highway Administration, 2018,[2] p. 3.

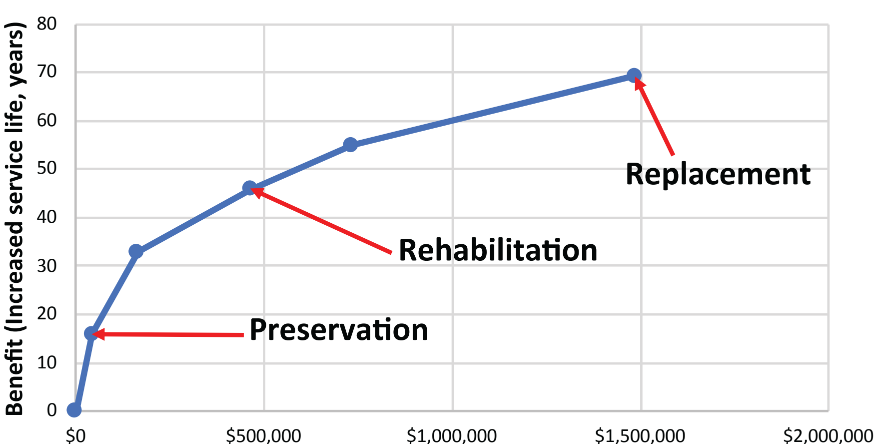

Figure 3. A benefit-cost comparison shows that well-chosen preservation actions can yield significant benefit at relatively low cost compared with rehabilitation or replacement projects. In this example, the benefit is measured in years of increased service life. Figure: Dave Juntunen.

(including no action) that can be taken for an individual bridge, or an entire network of bridges, can be compared over an analysis period to find the optimum treatment selections (actions). Proprietary software for BMSs, such as AASHTOWare Bridge Management, AgileAssets STRUCTURES ANALYST, and Deighton dTIMS, use concepts of benefit-cost analysis to optimize bridge asset management and strategic investment planning. Simply, this analysis begins by calculating the benefit-cost ratio for each possible action.

Any bridge manager can tell you that bridge preservation actions have an intrinsic value; however, it is not always obvious how to show this analytically. Fortunately, the tools available in BMSs and benefit-cost analysis can be used to show the value of bridge preservation. This is demonstrated in the following simple example, where we calculate and compare the benefit-cost ratio for a bridge replacement action and a bridge preservation action. BMSs have different methods to calculate benefit, which can be complex. For this example, we will simply measure benefit as added service life to the bridge and then use this measurement to calculate the benefit cost ratio $(\frac{B}{C})$ for two common bridge actions.

- Bridge replacement
  Added service life = 75 years
  Cost = $1.5 million

$$\frac{B}{C} = \frac{75}{1.5 \text{ million}} = 50 \text{ years per } \$1 \text{ million}$$

- Bridge preservation action
  Deck overlay
  Added service life = 15 years
  Cost = $50,000

$$\frac{B}{C} = \frac{15}{0.05 \text{ million}} = 300 \text{ years per } \$1 \text{ million}$$

We can see that the deck overlay action has a much higher benefit-cost ratio, which makes it the preferred action. When this type of analysis is done for all possible actions to all bridges in a network, mathematical procedures, such as incremental benefit-cost analysis or integer linear programming, can then be used to find the best combination of actions to maximize benefits given certain constraints, such as annual budget.

When benefit-cost analysis is done for a network of bridges, many owners have observed that well-chosen preservation actions frequently have higher benefit-cost ratios than rehabilitation or replacement projects, as shown in **Fig. 3**. A BMS can help determine the optimum portfolio of actions with the highest expected benefit within financial or other constraints.

BMSs and benefit-cost analyses are being used more frequently by state departments of transportation. Municipalities are also seeing the value of this type of management, which is not only limited to bridges. Agencies are starting to integrate bridge, pavement, sidewalk, stormwater, and other assets for overall infrastructure management. It is a great time to become familiar or reacquainted with benefit-cost analysis!

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The Current Slow Pace of Precast, Prestressed Concrete Bridge Innovation in the United States

by Gregg Reese, Modjeski and Masters

Prestressed concrete was arguably the most significant innovation in bridge construction in the 20th century. When a superior technology like this becomes widely used, methodologies are eventually established and further innovations become incremental rather than transformative.

In his work on modern economic history, economist Joseph Schumpeter characterized the concept of cycles of innovation as a series of waves.[1,2] Each wave represents the process of how a change progresses when new technologies that transform society are introduced. He described the process as occurring in three stages: invention, innovation, and diffusion. Invention is the research and development stage, innovation is the implementation stage, and diffusion occurs as the concept is successfully adopted and integrated into everyday life.

Prestressed concrete is now in the late diffusion stage and has become what is known as a "mature technology." As a result, innovation has slowed and there is resistance to further change. In recent years, I have witnessed a growing reluctance to consider even the simplest of new ideas in precast, prestressed concrete bridge construction, which is troubling.

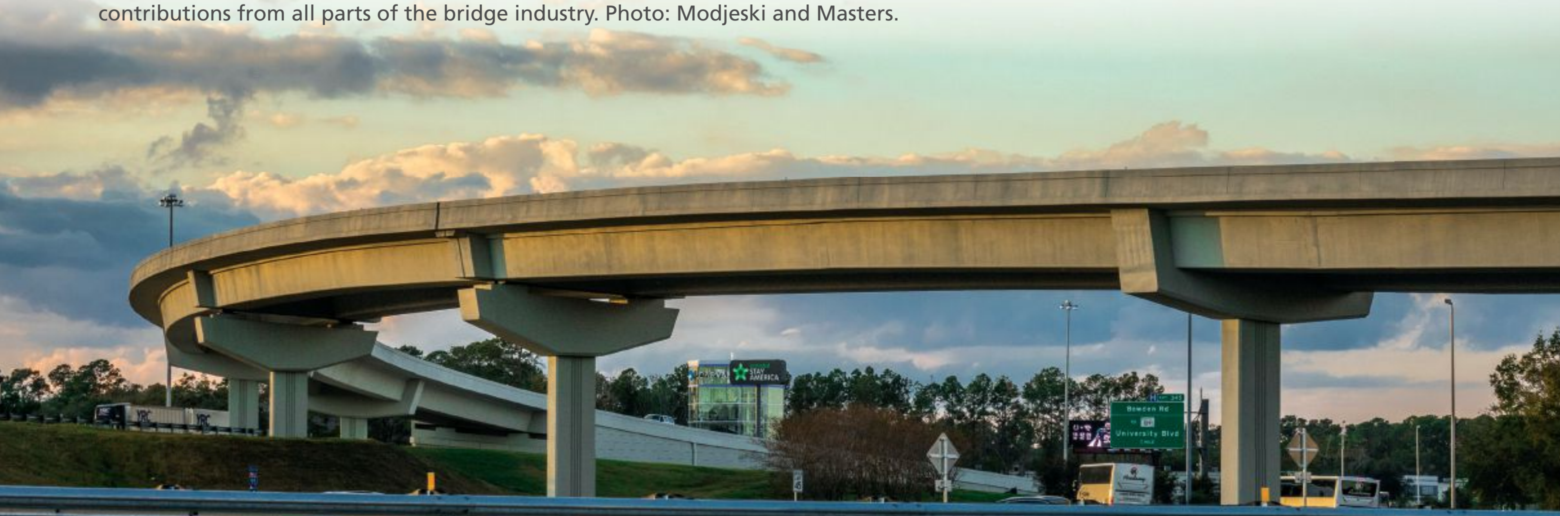
A mature technology represents a comfortable status quo. Human beings are predisposed to favor the familiar and resist change. For innovation to move into the marketplace, you need a compelling reason to abandon a comfortable status quo. The most common incentive is superior technology that produces significant financial advantage. Is that all it takes? Unfortunately, no. While superior technology and economic advantage are necessary, they are not sufficient in a risk-averse environment.

Economists and academics have studied resistance to innovation in construction and found that resistance manifests itself in many ways.[3] Innovation can be incremental and structural, but it can also be radical and disruptive. Innovation is perceived by many as a threat: change equals risk.

The construction industry has numerous barriers that discourage innovation. Most projects are constructed as a unique solution. The project is built by a temporary organizational team that is dismantled upon completion, and subcontractors and employees tend to scatter. Successful new ideas are often forgotten and frequently reinvented, but not established in the organization's culture.

Project delivery systems rely on low-cost selection that puts a premium on speed of construction. Work is performed by a fractured assortment of subcontractors and subconsultants working under a cascade of risk-shedding and risk-sharing contractual arrangements. Relationships among the contractor, designer, and owner tend to become adversarial, all of which results in an overreliance on "tried-and-true" methods and discourages risk taking and innovation.

The Southbound Interstate 95 to Eastbound State Road 202 (J. Turner Butler Boulevard) Flyover Bridge in Jacksonville, Fla., is an example of curved, spliced precast concrete U-girders that are post-tensioned to form continuous spans (see the Project article in the Winter 2018 issue of *ASPIRE*®). This innovative structure type was developed in Colorado in the 1990s and refined through contributions from all parts of the bridge industry. Photo: Modjeski and Masters.



A 230-ft-long ultra-high-performance-concrete (UHPC) U-girder being erected for the Setiawangsa-Pantai Expressway, part of the Duta-Ulu Kelang Expressway system in Kuala Lumpur, Malaysia. UHPC is a relatively recent innovation in the precast concrete industry. Photo: Dura Technology.

Infrastructure investment in the United States as a percentage of gross domestic product lags behind the rest of the developed world.[4] Funding has been inconsistent and has steadily declined since the mid-1960s. All of this results in a scarcity environment that discourages risk taking.

Innovation occurs when opportunity meets a champion operating in a supportive environment. Any stakeholder who sees an advantage in promoting a new idea and gets support can be a champion. Research has consistently shown that the most significant influencer in fostering innovation is the owner or client.[5] The essential elements of an environment that incubates new ideas are owners who are open to new ideas, future opportunities for use of an idea, and stakeholders who are willing to struggle through the learning curve and make necessary initial investments. Future projects are key; a one-off project is a tough sell. Finally, the idea itself must be worth the trouble and produce improved results and financial performance for the stakeholders.

What situations have successfully fostered a climate favorable to innovative ideas? Some examples follow.

- The Walnut Lane Bridge, completed in Philadelphia in 1951, was the first prestressed concrete bridge in the United States.[6] The project was constructed as a value-engineering option to a stone arch. The innovative design was bid at 30% cost savings to the city. The city chose a design concept that had never been used in the United States—a bold move that resulted in adoption of a new technology and had a game-changing effect on the interstate highway system and how we build bridges today.
- Segmental bridges were introduced in the United States in Texas[7] in 1972 (see the Project article about the JFK Memorial Causeway Bridge in the Summer 2021 issue of *ASPIRE*®) and California in 1974. In the late 1970s the Florida Department of Transportation committed to building four long bridges in the Florida Keys that were the first large-scale application of this technology.[8] The success of these projects inspired the industry to embrace segmental construction, making it a major force in bridge designs in the United States over the last 50 years.
- The Colorado Department of Transportation developed bridge design standards for curved precast concrete girders for interchanges and longer-span bridges in the late 1990s, and used those standards to successfully construct several bridges in the early 2000s. This is another example that illustrates how significant leadership by owners is to promoting Innovation (see related article in Summer 2015 issue of *ASPIRE*®). Since that time, this novel concept has been used on numerous projects over the last 20 years.
- Malaysia is currently a great incubator of bridge innovation. Yen Lei Voo, PhD, has designed and constructed more than 150 bridges in Malaysia over the last 10 years using ultra-high-performance concrete (UHPC) as the primary material (see related articles in the Summer 2016 and Spring 2017 issues of *ASPIRE*). This is an amazing achievement—nowhere else is this technology being used at a similar level. How did this happen? According to Dr. Voo, it was not easy, and UHPC had to prove its worth to be accepted. Early projects were designed as value engineering alternatives to more conventional designs. The UHPC designs were consistently more economical and resulted in superior solutions. Dr. Voo is convinced that without owner support, none of this would have been possible. Currently he is working on major projects in China and India as well as in Malaysia.

In summary, innovation is how we advance our world. Resistance to innovation is part of the process; it weeds out the bad ideas, but hopefully it does not kill the good ones. Precast, prestressed concrete can continue to be an indelible force in bridge construction if we, like those who came before us, have the courage to keep an open mind, be bold, and continue to try new things.

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PERSPECTIVE

WSDOT Policies and Criteria for Girders Damaged in Service

by Dr. Bijan Khaleghi, Washington State Department of Transportation

Every year in Washington state, several bridges experience overheight vehicle collisions. These collisions may result in damage to or failure of bridge girders or even collapse of the bridge system. The damage to precast, prestressed concrete girders may range from spalling and minor cracking of the bottom flange and web of a girder to loss of a major portion of a girder section. This article presents categories and criteria used by the Washington State Department of Transportation (WSDOT) for the assessment of structural damage to precast, prestressed concrete bridge girders caused by overheight collisions, and discusses guidelines to determine the repair or replacement of those girders that appear in Section 5.6.6 of the WSDOT *Bridge Design Manual*.[1]

Girder damage due to overheight collisions is relatively common in Washington state. **Figure 1** shows an example of the damage to the Interstate 5 (I-5) Chamber Way overpass bridge caused when a semitruck hauling a pair of excavators hit a portion of the bridge spanning southbound I-5 in Chehalis on July 22, 2016. The existing Chamber Way overpass was built in 1958 with a vertical clearance of only 14 ft 8 in. Though this clearance is adequate for the 14-ft-maximum vehicle height allowed without a permit, it does not meet the modern design standard of 16 ft 6 in. that is required for new construction highway crossings in Washington. Before the 2016 incident, this bridge had been damaged and repaired with strand splice anchors, as shown in **Fig. 2**. As a result of the significant structural damage incurred in 2016, WSDOT demolished the damaged span in its entirety (**Fig. 3**) and installed a temporary bridge until the replacement span could be constructed.

Repair of Damaged Prestressed Concrete Girders in Existing Bridges

Girder damage is divided into three categories: minor, moderate, and severe. The determination of the degree of damage to a prestressed concrete girder is largely a matter of judgment. Where the flange area has been reduced or strands lost, calculations can aid in making this judgment.

To determine the damage category and prepare the repair plan for bridges, the

Figure 1: In July 2016, a collision by an overheight vehicle damaged the prestressed concrete girder bridge over southbound Interstate 5 at Chamber Way in Chehalis, Wash. All Photos: Washington State Department of Transportation.

Figure 2: Before the 2016 collision, the same bridge had been damaged at the same location. The severed prestressing strands were repaired using strand splices (shown in inset photo and visible in the first girder in Fig. 1).

Figure 3: Because significant structural damage was incurred during the 2016 collision, the Washington State Department of Transportation demolished the damaged span in its entirety and installed a temporary bridge until the replacement span could be constructed.

location of damage and the size and extent of spalls and loose concrete are quantified and documented, and a sketch of the largest loss of cross section is prepared. Out-of-plane deformation is measured and reported as relative lateral deformation over a 10 ft length of girder. A crack map showing the orientation and width of all cracks, including those in the flanges, web, deck slab, diaphragms, and barrier walls, is included. Bridge bearings and expansion joints are inspected for any signs of damage, dislocation, or altered orientation.

The following sections present general damage categories, suggested repair procedures, and guidelines for the damaged girder conditions that require girder replacement.[1]

Minor Damage

Minor damage involves cracking and spalling, typically in the bottom flange, that may partially or fully expose at least one prestressing strand. However, no severed strands should be present. Strands with damaged, deformed, or kinked wire(s) should be considered severed, and this category would not apply.

To repair minor damage, the damaged area is to be thoroughly prepared, coated with an epoxy bonding agent and repaired to the original cross section with grout equal in strength to the original concrete. All cracks wider than 0.006 in. should be injected with epoxy.

Moderate Damage

This category of damage involves localized loss of between 25% and 50% of the cross section, no damage to the interface shear reinforcement, no cracking observed near the supports due to girder deformation, and girder sweep (at the top flange) that is less than ⅛ in. per 10 ft. Under the moderate damage category, the moment strength would generally be unchanged despite the damage, but service level stresses would change.

Patching, with the same procedures outlined for the minor damage cases, may be required. Inject all cracks that are wider than 0.006 in. with epoxy. If the interface shear reinforcement is damaged, it should be repaired or restored. If it is determined that patching of the top flange is required, and there is no existing transverse steel in the top flange, anchorage bars installed with epoxy adhesive may be provided, as required by structural calculations, before patching. As a general guide, ½-in.-diameter adhesive anchors at 6 in. spacing should be considered.

If damage is moderate, it is probable that some prestress will have been lost in the damaged area due to reduction in concrete cross section and consequent strand shortening, or through loss of strands. If the damage does not exceed the criteria for girder replacement, a repair procedure should be developed according to the following guidelines.

1. **Determine condition:** Determine the stress in the damaged girder due to the remaining prestress and loads in the damaged state. If severe overstresses are found, action must be taken to restrict loads on the structure until the repair has been completed. If the strand loss is so great that the stress limitations in Article 5.9.2 of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[2] cannot be met with the remaining strands, replacement of the girder should be considered.
2. **Restore prestress if needed:** Prestress in damaged and severed strands can sometimes be restored with mechanical strand couplers. Damaged girders with broken 0.6-in.-diameter strands may need to be repaired with 0.5-in.-diameter strands and additional post-tensioning. Current commercially available couplers are capable of restoring full prestressing force in strands of up to 0.5-in. diameter. Verify that the restoration of full prestressing force will not cause overstress in the damaged girder section.
3. **Prepare a repair plan:** Draw a sketch to show the area of concrete removal required for replacement, and for the installation of any required mechanical strand couplers. The damaged area is to be thoroughly prepared, coated with an epoxy bonding agent, and repaired with grout equal in strength to the original concrete.

Severe Damage

Severe damage involves localized loss of greater than 50% of the cross section, extensive damage to the interface shear reinforcement, or out-of-tolerance sweep of the top flange of the girder.

Although repair may be possible in some cases classified to this damage category, any such repairs should be considered only after careful review of structural strength, serviceability, and stability considerations. Otherwise, replacement of the girder(s) should be considered. If there is excessive girder sweep, replacement may be the only practical option.

Girder Repair versus Replacement

Several factors need to be considered when evaluating whether to repair or replace a damaged girder. Among them are the extent of concrete damage, the number of broken strands, the location and magnitude of web damage, permanent offset of the original girder alignment, and overall structural integrity.

The following guidelines describe girder conditions that require replacement.

- **Strand damage:** If more than 25% of prestressing strands are damaged or severed, replacement is required. Although splicing is routinely done to repair severed strands, there are practical limits as to the number of couplers that can be installed in the damaged area.
- **Girder displacements:** If the bottom flange is displaced from its original horizontal position by more than ½ in. per 10 ft of girder length, the alignment of the girder has been permanently altered by the impact and replacement is required. Examples of nonrepairable girder displacement include cracks at the web-flange interface that remain open. Abrupt lateral offsets may indicate that stirrups have yielded. A girder that is permanently offset may not be restorable to its original geometric tolerance by practical and cost-effective means.
- **Concrete damage at the harping point:** If concrete damage at the harping point results in permanent loss of prestress, girder replacement is required. Severe damage at the harping point would include any damage such that the hardware and strands have moved significantly. Extreme cracking or major loss of concrete near the harping point may indicate a change in strand geometry and loss of prestress. Such loss of prestress in the existing damaged girder cannot be restored by practical and cost-effective means, so girder replacement is required.
- **Concrete damage at girder ends:** If there is severe concrete damage at girder ends resulting in permanent loss of prestress or loss of shear capacity, girder replacement is required. Extreme cracking or major loss of concrete near the end of a girder may indicate loss of strand bond with the concrete and loss of prestress, or a loss of shear capacity.
- **Significant concrete loss from the web:** If significant concrete damage in the web results in loss of shear capacity, girder replacement is required. The web damage shall be considered significant when more than 25% of the web section is damaged or when shear reinforcement has yielded.

There are other issues that do not automatically trigger replacement but require further consideration and analysis. These issues include significant concrete loss from the bottom flange, the capacity of adjacent undamaged girders, repairs to previously damaged girders, and the cost of repair versus replacement. The WSDOT *Bridge Design Manual*[1] provides additional guidance on evaluating girder or superstructure replacement.

Girder Replacement Considerations

The WSDOT *Bridge Design Manual*[1] requires that damaged girders be replaced in accordance with current WSDOT design criteria and with current girder series. The replacement girder should be of the same type or the same depth as the original damaged girder. Furthermore, replacing a damaged girder involves some care in determining a proper replacement sequence. In general, the procedure consists of cutting through the existing deck slab and diaphragms and removing the damaged girder. Adequate exposed reinforcing steel must remain in the deck slab and diaphragms to allow splicing to new reinforcement.

It is important that the camber of the new girder match that of the existing girders that remain. Excessive camber of the new girder can result in inadequate deck-slab thickness. Girder camber can be controlled by prestress, curing time, or dimensional changes.

When a damaged girder is replaced, the intermediate diaphragms adjacent to the damaged girder shall be replaced with full-depth diaphragms and the replacement girder should be of the same type or the same depth as the original damaged girder. Casting the new bridge deck and diaphragms simultaneously to avoid overloading the existing girders in the structure should be considered. Extra bracing of the replacement girder at the time of bridge deck placement will be required.

Conclusion

It is not uncommon for prestressed concrete girders to be damaged by collisions caused by overheight vehicles. WSDOT has developed criteria to evaluate the severity of the damage and whether the girders should be repaired or replaced. The guidelines presented in this article are intended to help engineers exercise the judgment required to make decisions regarding the repair of damaged prestressed concrete girders.

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1. Washington State Department of Transportation (WSDOT). 2020. *Bridge Design Manual*. M23-50.20. Olympia: WSDOT. https://www.wsdot.wa.gov/publications/manuals/fulltext/M23-50/BDM.pdf
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EDITOR'S NOTE

Bridge damage due to overheight vehicle strikes is a common occurrence throughout the United States. There is a pending National Cooperative Highway Research Project (NCHRP) to develop a Guide for Preventing and Mitigating the Risk of Bridge and Tunnel Strikes by Motor Vehicles *to help state departments of transportation, public safety agencies, and the motor carrier industry prevent these events. More information can be found at https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4950.*

Other resources are available for the evaluation and repair of prestressed concrete girders with impact damage. One such resource is the Guide to Recommended Practice for the Repair of Impact-Damaged Prestressed Concrete Bridge Girders, *developed by Harries et al. for NCHRP Project 20-07, Task 307. It was published in 2012 and can be found at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07(307)_AppendixA-GUIDE.pdf. The final report on the project is available at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07(307)_FR.pdf.*

The Aesthetics of Short- and Medium-Span Bridges

by Frederick Gottemoeller

Bridges over dramatic canyons or other memorable natural features are actually the easiest to make attractive, as the site itself offers features which the bridge can (and must) react to. Such bridges often require long spans (greater than 150 ft), so there are opportunities to shape the structural elements in ways that attract attention. Bridges with spans less than 150 ft, especially those in flat terrain that pass low over railroads, wide stretches of water, or other highways, offer fewer opportunities to create aesthetic interest. So, how can the appearance of such bridges be improved?

It's hard to beat the economy of precast concrete beams for spans of less than 150 ft. Notwithstanding their considerable economic and functional benefits, precast concrete beams don't offer much for people's aesthetic imaginations to latch on to. So, designers have to look to other elements of the bridge—piers, abutments, parapets, railings, and even the lighting and landscaping—to capture people's attention.

The place to start is to identify the audience: who will be seeing the bridge, and from where? For a bridge over a highway, one audience will be the users of the undercrossing highway. The occupants of vehicles on that highway will be moving at approximately the speed limit of that road. Their ability to see and appreciate the features of the bridge will be limited compared with that of users of the sidewalks on the overpass, who will have time to notice details and stop to appreciate particular features.

If a bridge spans a riverside path or park, its audience will not only have time to appreciate its features but will also have higher expectations. They will want the bridge to respect the natural features that they are enjoying as they walk. Finally, pedestrians *on* the bridge will want to enjoy the view from the bridge, as well as the details of the railings and sidewalks.

Bridges over wide rivers, lakes, or bays have an additional audience: people on the riverbanks upstream and downstream, or along the lake or bay shore, who can see the bridge from their homes, offices, or nearby bridges. They will want the bridge to be aesthetically attractive and to be a scenic asset within whatever landscape or civic space the bridge occupies.

Because every bridge has its own unique combination of audiences, it's impossible to offer a one-size-fits-all set of recommendations. Instead, here are three examples that can serve as inspiration.

1. Typical ramp pier: an economical way to add aesthetic interest to a simple pier design

For low bridges in rural areas, where the audience for the bridge is relatively small, or for highway overcrossings, where the audience is moving too fast to appreciate much detail, there is still a need to make the bridge attractive in some economical way. The pier shown in **Fig. 1** demonstrates several ways of doing that. The top of the pier is flared outward to achieve sufficient width without a pier cap or stub cantilever. The result is a geometrically simple shape that viewers can quickly grasp and that is easy to form. The edges are chamfered, making the pier seem narrower. And there is a very simple pattern of vertical grooves to add visual interest. The pattern also makes the pier appear narrower. Note that this particular pier carries a box girder, but it could as easily carry U-beams or other precast concrete girders.

The same techniques can be applied to a pier for a wider bridge. For example, on a wider pier, the pattern of grooves could be repeated once or twice, with similar positive effects. The basic principle is to make the pier a unified, geometrically simple shape, and then enhance its appearance with easily formed refinements, such as the chamfered edges and vertical-groove patterns.

Of course, there are many possible refinements. For example, if the grooves are split in the center at the level where the flare begins and diverted to follow the flared edges of the pier, the result would be an inverted triangle of smooth concrete at the top center of the pier. Deciding whether that improves the pier's appearance is up to the designer. They can exercise their own tastes on an element that will have a large impact on appearance but very little impact on the final cost.

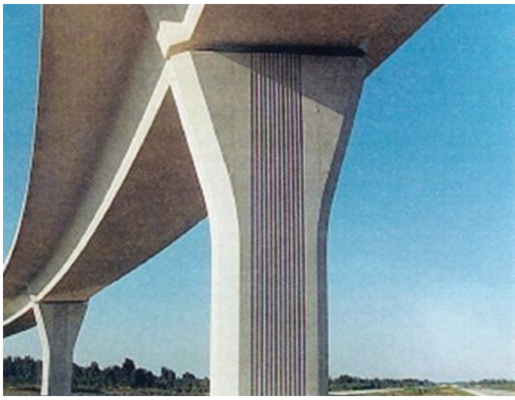

Figure 1. A simple geometric shape with a simple pattern of vertical grooves makes this pier both visually interesting and economical. Photo: Frederick Gottemoeller.

2. Stewart Street Bridge, Dayton, Ohio: a low bridge over a wide river combining 85- and 25-ft-long precast concrete box beams with custom piers, parapets, railings, and lighting

Dayton's rivers are wide but not deep, allowing fairly short spans that are well within the range of standard precast concrete beams. Beams such as those used here are the default choice for new superstructures because of their overwhelming cost advantages. The challenge for designers is how to economically add visual character to these city-center bridges. In the case of the Stewart Street Bridge (**Fig. 2**), this challenge inspired some creative thinking about the piers, parapets, and lighting.

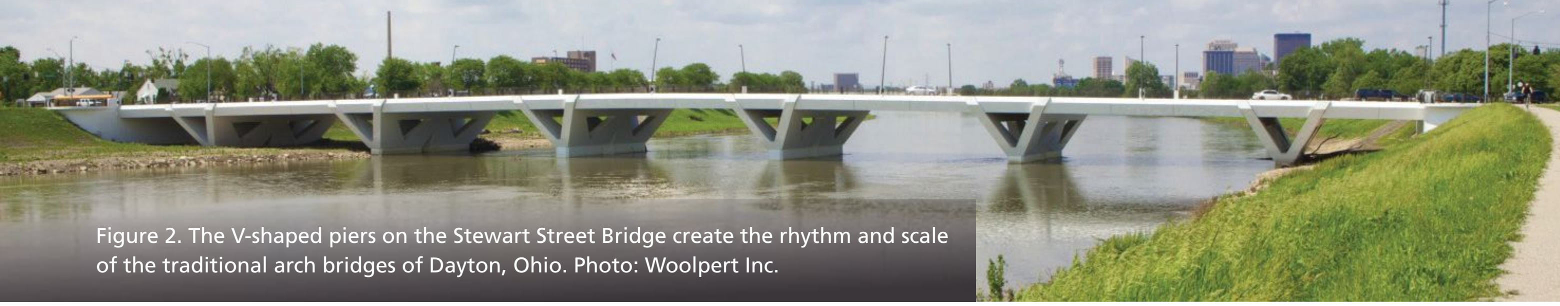

Figure 2. The V-shaped piers on the Stewart Street Bridge create the rhythm and scale of the traditional arch bridges of Dayton, Ohio. Photo: Woolpert Inc.

The bridge is adjacent to the University of Dayton's new research campus, so the city wanted a bridge with a contemporary appearance as well as the rhythm and scale of the filled-arch bridges that were Dayton's historic solution. A V-shaped pier provides a repeated, standardized, easy-to-build element that economically meets this goal. The pier creates 110-ft spans with 85-ft-long, 42-in.-deep precast concrete box beams between the piers and similar precast concrete box beams connecting the tips of each V providing the remaining 25 ft of each span. The necessary variation in pier height was created not by widening or lengthening the V, but by lengthening the vertical stem at the bottom of each V, which allowed all of the Vs to be cast using a single set of standardized forms. The triangular openings in the slanted cross wall lighten the visual (and physical) weight of the piers and make them more transparent.

A cast-in-place concrete fascia covers and unites the edge beams. As a continuation of the angular theme of the V-piers, the face of the fascia is split horizontally into two slanted planes. The upper plane is slanted toward the sky and catches more light, while the bottom plane is slanted toward the river and is darker. The result is a bright horizontal band sweeping from bank to bank, interrupted just briefly at the piers. Even the highway lighting poles are slanted to pick up the angular theme. The inverted pyramidal spaces within the piers create opportunities for colored LED lighting that reflects off the river and enlivens the nighttime appearance of that whole reach of the river (**Fig. 3**). (See the Summer 2011 issue of *ASPIRE*® for more information on this bridge.)

Figure 3. Colored LED lighting within the V-shaped piers of the Stewart Street Bridge enliven the nighttime appearance of the Great Miami River in Dayton, Ohio. Photo: Woolpert Inc.

3. **NJ 52 over Great Egg Harbor Bay, Ocean City, N.J.: a long bridge over water combining 140- to 160-ft standardized bulb-tee girders with custom piers and LED lighting**

For a long bridge over water, the appearance of multiple piers, seen all at the same time, is a major aesthetic opportunity. In this structure (**Fig. 4**), the striking Y-shaped piers are adapted to changing pier heights by simply lengthening the shaft. The "branches" of the Ys at the tops of the piers are all the same, which allowed all of the Ys to be cast in standardized forms. The faces of each pier are split vertically into two halves. Each half is in a different plane, so that the plan section of the shaft resembles a bow tie. Each face catches the light differently, so that one half seems brighter than the other. The geometry of these angled planes also creates a slight taper in the Y branches, so that they widen slightly as they meet the pier cap. The overall effect is to make the pier seem both slimmer and more interesting.

Finally, the soffit of the pier cap between the branches of the Y is a convenient place to mount a simple LED light strip. From this location, the light strip can illuminate not only the void within the branches but also the shaft of the pier itself. The LED lights are programmed to change color in timed sequences, so that waves of color appear to be moving across Great Egg Harbor Bay (**Fig. 5**). (See the Winter 2013 issue of *ASPIRE* for more information on this bridge.)

These three examples show how creative shaping of piers, parapets, and lighting can create a striking bridge even with standardized superstructure elements. Similar effects can be obtained by customizing abutment features and landscaping. Decisions about which features of a bridge to emphasize give designers an opportunity to exercise their imaginations and tastes. Of course, their choices should be rooted in structural efficiency and economy, while also recognizing the context of the bridge as well as the needs and expectations of the audiences who will be using and seeing the bridge.

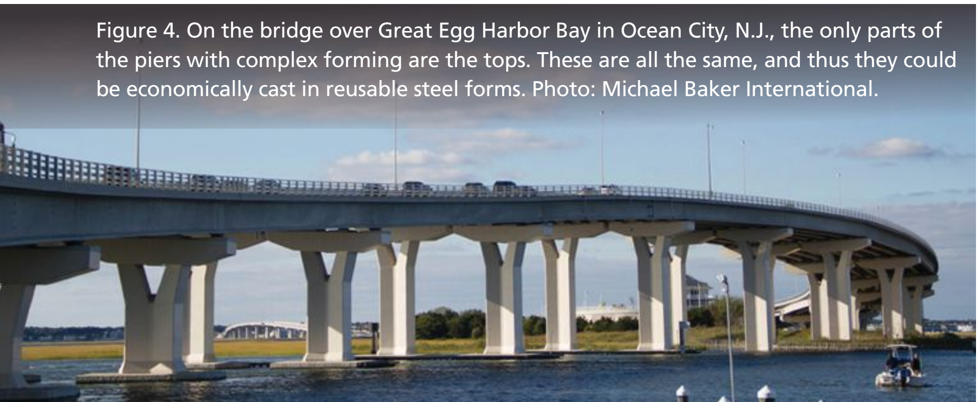

Figure 4. On the bridge over Great Egg Harbor Bay in Ocean City, N.J., the only parts of the piers with complex forming are the tops. These are all the same, and thus they could be economically cast in reusable steel forms. Photo: Michael Baker International.

Figure 5. Timed sequences of color change in the LED pier lighting produce the illusion of waves of color moving across Great Egg Harbor Bay. Photo: Michael Baker International.

PROJECT

New Long X Bridge Merges History with Modern Design

by David Finley and members of the Bridge Division, North Dakota Department of Transportation

The historic Long X Bridge was originally built in 1959 as a two-lane Warren through-truss bridge along U.S. Highway 85 (U.S. 85) over the Little Missouri River. Located in the scenic Badlands of North Dakota, the bridge is named to pay tribute to the Long X Ranch, the largest cattle ranch in McKenzie County in the 1880s era of cattle drives and open range in Dakota Territory, and the Long X Trail, a route used to move cattle from southern parts of the country to eastern Montana and western North Dakota. Both the ranch and the trail are staples of the state's Western heritage and ranching culture.

The bridge serves as a gateway to the north unit of the Theodore Roosevelt National Park and the Bakken oil formation, one of the largest oil developments in the country. This heavily traveled corridor plays a vital role in the economic development and tourism industry for the state.

In July 2019, the North Dakota Department of Transportation (NDDOT) began a two-year, $37 million project consisting of 1.77 miles of highway reconstruction, including replacement of the Long X Bridge on a new alignment east of the existing bridge, and construction of North Dakota's first wildlife crossing built underneath U.S. 85.

The new Long X Bridge is a five-span prestressed concrete girder bridge, which accommodates two 12-ft driving lanes in each direction, and a concrete median barrier. The four-lane bridge is designed to accommodate the heavier loads of today's truck traffic while also removing the original structure's horizontal and vertical clearance restrictions. The new bridge plays an integral role in the upcoming 62-mile, four-lane expansion project from Watford City to Interstate 94 on U.S. 85.

Traffic on U.S. Highway 85 and half of the new Long X Bridge over the Little Missouri River as the old bridge is deconstructed. All Photos and Figures: North Dakota Department of Transportation.

profile

U.S. HIGHWAY 85 BRIDGE OVER THE LITTLE MISSOURI RIVER AND WILDLIFE CROSSING / NEAR WATFORD CITY, NORTH DAKOTA

DESIGN ENGINEERS: Highway bridge: North Dakota Department of Transportation (NDDOT), Bismarck, N.Dak.; south abutment foundation design: Shannon & Wilson Inc., Denver, Colo. Wildlife crossing: NDDOT, Bismarck, N.Dak.; Contech Engineered Solutions LLC, West Chester, Ohio; Civil Design Professionals, Bloomington, Minn.

CONSTRUCTION ENGINEER: AECOM, Bismarck, N.Dak.

PRIME CONTRACTOR: Ames Construction, Burnsville, Minn.

PRECASTERS: Bridge beams: Forterra Building Products, Menoken, N.Dak., and Elk River, Minn.—a PCI-certified producer Wildlife crossing arch structure: Forterra Building Products, Rapid City, S.Dak.—a PCI-certified producer

SPECIALTY CONTRACTOR: Drilled shafts and post-tensioned ground anchors: Malcolm Drilling Company, Salt Lake City, Utah

Construction of the new Long X Bridge on U.S. Highway 85 over the Little Missouri River in the Badlands of North Dakota. Girders for all five spans have been erected, and epoxy-coated reinforcement is being placed for the cast-in-place concrete deck at the far end.

Girders have been erected for the first span of the new Long X Bridge. Formliners were used on all piers to simulate stonework. Wall-type piers were used to limit debris blockage in the channel.

"The completion of the bridge and wildlife crossing will greatly enhance the efficiency of the transportation system in the state," says NDDOT director Bill Panos. "While our number one priority is always safety, we also want to provide the best experience possible for the traveling public."

The State of North Dakota and the NDDOT are investing in this corridor to ensure it is a safe and accessible passageway through the western part of the state. Two lanes of the bridge were officially opened to traffic in October 2020, and the project was fully opened as of June 2021.

"We recognize that U.S. Highway 85 and the Long X Bridge are essential to the transportation needs in western North Dakota," says Panos. "This bridge will serve as an economic development tool, and was an amazing engineering and community effort from our team, the contractors, and all cities in the area."

End of an Era

It became apparent over a decade ago, during the state's oil boom, that the old Long X Bridge could no longer accommodate the current traffic volume.

In fact, during the peak of the boom, more than 4200 vehicles crossed the structure daily, with the majority being truck traffic from the oil and agriculture industries. Many trucks transporting oversized or overweight loads were unable to cross the structure due to width, height, and weight restrictions.

Overheight vehicle strikes to the bridge were frequent, and the damage created lengthy closures and costly repairs for the state. The temporary closures resulted in detours up to 75 miles long, adding considerable travel time and costs for motorists.

"The old bridge was a bottleneck for moving oversize freight into the region," says NDDOT state bridge engineer Jon Ketterling. "Not only did it limit loads traveling on this important highway, but the bridge was also often damaged by overheight loads. It was clear to us that the bridge needed to be replaced, and we made it a priority."

These issues, along with the age of the bridge, ultimately led NDDOT to move forward with a redesign with no overhead clearance limitations. According to Ketterling, moving away from the overhead truss system eliminates all of the height restrictions once associated with the Long X Bridge, allowing traffic to flow more easily through U.S. 85 and western North Dakota.

The New Bridge

The new Long X Bridge is 790 ft long and 85 ft wide. It has two 40-ft divided clear roadways and ample room to accommodate the current traffic volume and the wider loads that need to move along this corridor.

The bridge substructure units are supported on steel H piling, except for

NORTH DAKOTA DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: Four-lane, 790-ft-long, 85-ft-wide, five-span prestressed concrete I-beam bridge with cast-in-place deck; nearby wildlife crossing with proprietary twin-leaf precast concrete arch system, 60-ft-wide span, 18 ft rise, 150 ft long

STRUCTURAL COMPONENTS: Bridge: 8-in.-thick cast-in-place concrete deck, sixty 81-in.-deep prestressed concrete I-beams; 7 steel-encased drilled shafts (8 ft diameter × 130 ft) and 145-ft-long ground anchors supporting the cast-in-place concrete south abutment, pile-supported cast-in-place concrete north abutment and piers, cast-in-place concrete diaphragms and approach slabs. Wildlife crossing: fifty 6-ft-wide precast concrete half-span arch segments on pile-supported cast-in-place concrete footings, mechanically stabilized earth headwalls and wingwalls

OTHER MATERIAL SUPPLIERS: Bridge abutment ground anchors: Dywidag-Systems International USA Inc., Bolingbrook, Ill. Wildlife crossing: mechanically stabilized earth wing walls and headwalls keystone retaining wall systems: Kanta Products Inc., Three Forks, Mont.

CONSTRUCTION COSTS: Bridge: \$17.34 million (\$256/ft^2); wildlife crossing: \$3.08 million (\$338/ft^2); total project cost: \$33.97 million

One span of 81-in.-deep precast concrete beams has been erected as construction of the piers continues on the new Long X Bridge. Delivery trucks were able to use the construction causeway to get girders near their placement span. Two cranes were used to lift the ends of the beams and walk them to their final location.

the south abutment, which is supported on 8-ft-diameter drilled shafts. The pier aesthetics were chosen to reflect the historic nature of the original structure and scenic setting. Pile-driving restrictions were in place due to the proximity of the bridge to Theodore Roosevelt National Park, and a privacy fence was constructed between the worksite and the park to obstruct the view of the construction site from the park. There was also a spawning restriction in place that limited work in the river during certain times of the year. A 50-ft-wide opening in the channel was required at all times.

The superstructure consists of an 85-ft-wide, 8-in.-thick cast-in-place concrete deck supported on sixty 81-in.-deep, 156-ft-long prestressed concrete I-beams. The fabricator made modifications to the original beam design to accommodate stresses during transportation. Some beams were produced in Elk River, Minn., and some were produced in Menoken, N.Dak.

The bridge geometry is straightforward, with a tangent horizontal alignment and a vertical alignment with a constant grade of –1.47% from south to north along the length of the bridge.

The design strengths of the concrete are 3000 psi for the substructure, 4000 psi for the superstructure and drilled shafts, and 8000 psi for the precast concrete beams.

The bridge required nearly 5500 yd^3 of concrete, more than 9300 ft of precast concrete girders, and nearly 940,000 lb of reinforcing steel.

"We are extremely proud of the work our engineers and contractors put into this project," says Panos. "The amount of time and effort that went into making this project possible truly shows the commitment and professionalism of everyone involved."

Construction Challenges in the Badlands

When designing and building the bridge, the variety of soil conditions present in the Badlands required engineers to accommodate constantly shifting terrain. In fact, part of the bridge is located on an active landslide.

"The soil conditions were investigated thoroughly beforehand and were planned for through the contract documents," says Ketterling. "The new bridge has a unique design to account for the on-site soil conditions."

Inclinometer readings indicated movement near the south abutment of the existing bridge at a depth of about 50 ft. The NDDOT elected to design the south abutment of the bridge to resist landslide loading using drilled shafts tied-back with ground anchors.

"The south abutment was founded on five 8-ft-diameter drilled shafts that required anchoring to resist the ground instability detected in this area," says Ketterling. "In addition, ground monitoring sensors were installed to detect future soil movement."

The key was to resist landslide loads and not to stabilize the landslide, which would be nearly impossible because of the volume of the landslide mass above the south abutment. By allowing the bridge foundations to resist future movement of the ground as it flows around the foundations, the design was more economical than attempting to stabilize the hillside with a conventional factor of safety.

The design incorporated an outboard, non-load-bearing drilled shaft outside of the bridge footprint. This innovative solution was implemented because three-dimensional analyses showed that

Precast concrete arch segments are erected for the wildlife crossing beneath U.S. Highway 85. The arch provides a 60-ft-wide, 18-ft-tall space to accommodate wildlife passage.

Pier construction on the new Long X Bridge.

The completed new four-lane Long X Bridge on U.S. Highway 85 over the Little Missouri River. The temporary construction causeway has been removed and the river channel has been restored.

The replacement of the Long X Bridge was part of a $37 million North Dakota Department of Transportation project that included 1.77 miles of highway reconstruction as well as construction of North Dakota's first wildlife crossing built underneath U.S. Highway 85.

the inner shafts received less load than the outboard shaft, which attracted higher loading in a flowing ground scenario.

The total post-tensioning force for the 15 ground anchors was 2775 kip with the 185-kip lock-off load at each anchor. All the ground anchors were proof-tested at higher loading.

Wildlife Crossing

When transitioning the roadway from two lanes to four, the NDDOT placed a focus on roadway safety and worked with its partners to help reduce animal-vehicle collisions. A wildlife crossing featuring a precast concrete tunnel under U.S. 85 was built just south of the new Long X Bridge.

The structure consists of a proprietary twin-leaf arch system comprising fifty 6-ft-wide precast concrete half-arch segments supported on a cast-in-place, pile-supported foundation. Because the soils in this region are highly erodible, the foundation is supported by 80 HP14x89 steel piles. The roadway embankment is retained using mechanically stabilized earth headwalls and wingwalls.

The 150-ft-long structure was designed to provide a 60-ft-wide span and an 18-ft-tall space to accommodate wildlife passing under U.S. 85. "It was determined that bighorn sheep need a clear opening of 15 ft high by 40 ft wide for the animals to feel comfortable enough to move through the crossing," says Ketterling. This design is the first of its type in North Dakota and provides a better passageway for area inhabitants such as bighorn sheep, elk, and deer.

"The North Dakota Badlands is a prime habitat for many wildlife species, especially bighorn sheep," says Ketterling. "After conducting a wildlife assessment and consulting with agencies during the environmental process, it was decided the wildlife crossing was necessary to ensure connectivity of the bighorn sheep habitat and to reduce animal-vehicle collisions."

It is estimated that there are 3200 animal-vehicle collisions each year in North Dakota, resulting in $50 million per year in vehicle damage/repairs, insurance claims, hospital bills, towing, cleanup, and value associated with wildlife. The goal of this crossing is to help reduce these numbers and improve safety along the corridor.

Fate of the Old Bridge

The original Long X Bridge was eligible to be listed in the National Register of Historic Places. For this reason, the south span of the through truss was put up for adoption and will be preserved by a North Dakota rancher. This 250-ft-long section of the old Long X Bridge has been relocated to the adoptee's property and will be subsequently reconstructed over the Beaver Creek southeast of Linton.

"The old Long X Bridge served the public well over the last 60 years, and it is nice to see a small portion of its history live on," says Panos.

David Finley is external communications manager for the North Dakota Department of Transportation in Bismarck.

The south abutment of the new bridge has a unique design to account for shifting soil conditions. The south abutment is founded on five 8-ft-diameter drilled shafts that are anchored to resist landslide loading. Ground monitoring sensors were installed to detect future soil movement.

Atkinson Boulevard Over CSXT Railroad and Interstate 64

Concrete provides economic and durable new east-west link

by Timothy Beavers, Caroline Hemp, and Jeremy Schlussel, Whitman, Requardt & Associates LLP

Since the mid-1980s, the comprehensive plan for Newport News, Va., included a new four-lane east-west connector between Warwick Boulevard and Jefferson Avenue to address future needs for cross-peninsula traffic movements. This new roadway would be required to span the CSX Transportation (CSXT) railroad and Interstate 64 (I-64) and traverse a large, forested area with wetlands throughout. To bring this road to fruition, numerous alignment studies were performed to determine the most appropriate corridor that would have the least environmental impact while also providing an economic and durable connection. Key goals were to reduce the roadway's impact on wetlands, limit long-term maintenance and construction costs, constrain superstructure depths, and keep fills to a minimum. The decisions resulting from these goals led to the creation of the longest continuous, prestressed concrete bulb-tee beam bridge in Virginia. Owing to the hard work of the city staff managing the design and construction, the designer's attention to detail, and the contractor's proactive planning and collaboration, this new, vital transportation link was successfully completed, and a grand opening was held on December 8, 2020. The bridge was funded through the Virginia Department of Transportation (VDOT) with city, state, and federal funding contributions.

Project Description

The bridge is 1742 ft 6 in. long with a 27.5-degree skew and an out-to-out width of 75 ft that carries four travel

A train passes under a beam that had just been placed over the busy CSX Transportation railroad line. A chain hold-down at the beam end on the pier provided positive restraint. Photo: Whitman, Requardt & Associates.

profile

ATKINSON BOULEVARD OVER CSXT RAILROAD AND INTERSTATE 64 / NEWPORT NEWS, VIRGINIA

BRIDGE DESIGN ENGINEER: Whitman, Requardt & Associates LLP, Richmond, Va.

OTHER CONSULTANT: Surveyor: Precision Measurements Inc., Newport News, Va.

PRIME CONTRACTOR: Joint venture of Bryant Contracting Inc., Toano, Va. (bridge), and Basic Construction Company LLC, Newport News, Va. (roadway)

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

Aerial view of the Atkinson Boulevard Bridge looking east. Photo: New Media Systems and Whitman, Requardt & Associates.

Lightweight concrete being placed in the deck. VDOT Class III (stainless steel) reinforcement was used in the concrete deck and barriers. Photo: Whitman, Requardt & Associates.

lanes and a shared-use path. The superstructure cross section consists of eight 85-in.-deep prestressed lightweight concrete bulb-tee beams spaced at 9 ft 11 in. with a composite 8½-in.-thick lightweight concrete deck. The lightweight concrete specified for both the beams and concrete deck had a 120 lb/ft^3 maximum density. The bridge consists of 12 spans made continuous for live load. The bridge substructure elements use normalweight concrete and feature two "Virginia abutments" to account for expansion and contraction. The 11 cap-and-column concrete piers reach up to 40 ft tall, and the two piers adjacent to the CSXT railroad were designed with a crash wall. The substructure is supported by 520 plumb 16-in.-square prestressed concrete piles totaling over 27,000 linear ft. In addition, the approach roadway is supported by mechanically stabilized earth (MSE) walls totaling 1274 ft in length.

Why Concrete?

The goal of the bridge design was to create an economical, durable, resilient, and low-maintenance bridge structure. During the initial study phase, three major design concepts were developed: a fully continuous concrete superstructure, a fully continuous long-span (180 ft minimum) structural steel superstructure, and a two-bridge solution with one bridge crossing over the CSXT railroad and the other crossing I-64 east- and westbound, connected by a nearly 50-ft-tall and approximately 900-ft-long MSE wall. At the time of the study in 2015, structural steel was in high demand, resulting in reduced availability and premium cost. The two-bridge option was deemed not viable because of the poor soil conditions at the MSE infill location and the associated impacts. After review with the city and permitting agencies, the fully continuous prestressed concrete bulb-tee beam bridge was chosen.

Once the fully continuous concrete superstructure had been selected, the goal was to ensure that the final layout would span the CSXT right-of-way and

The bridge has two "Virginia abutments" that allow for contraction and expansion while protecting the beam ends and bearings with a concrete end diaphragm. Roadway drainage is collected in the concrete trough and directed away from the bridge structure. Photo: Whitman, Requardt & Associates.

CITY OF NEWPORT NEWS, VIRGINIA, OWNER

OTHER MATERIAL SUPPLIERS: Lightweight aggregate: Carolina Stalite Company, Gold Hill, N.C.; stainless steel reinforcement: Transcon Supply, Harrisonburg, Va.; elastomeric bearings: Cosmec Inc./Dynamic Rubber, Athens, Tex.; mechanically stabilized earth walls: Reinforced Earth Company, Reston, Va.

BRIDGE DESCRIPTION: A 1742-ft 6-in.-long, 12-span, fully continuous (joints only at abutments) prestressed lightweight concrete bulb-tee beam bridge

STRUCTURAL COMPONENTS: All spans used eight lines of prestressed lightweight concrete 85-in.-deep bulb-tee beams up to 156 ft long with an 8½-in.-thick cast-in-place lightweight concrete deck with lightweight concrete end diaphragms and continuity diaphragms; cast-in-place concrete pier caps, columns, and footings; and 16-in.-square prestressed concrete piles

BRIDGE CONSTRUCTION COST: $22.7 million ($173.70/ft^2)

allow for future widening of I-64. The designers optimized the layout over the CSXT railrod and I-64 east- and westbound to lay out three spans that were geometrically similar. Lightweight concrete was selected during the early part of the final design efforts. The use of lightweight concrete deck and girders allowed the designer to remove a beam line while keeping the same 85-in. beam depth, and to reduce substructure loads to help optimize the length of the numerous prestressed concrete friction piles. The optimized spans measured 156 ft 2 in. from centerline of pier to centerline of pier. The remaining nine spans were chosen as an economic balance between number of piers and the span limitations of the 85-in. bulb-tee beams. With the use of concrete elements and standard detailing, the bridge-only costs proved to be very economical, with an as-bid price of approximately $175 per square foot of bridge deck.

Technical Design Details and Unique Features

While this project was designed and constructed for the City of Newport News Department of Engineering, standard VDOT details were used extensively to help keep construction costs down and to reduce future maintenance costs. Although the bridge used standard elements, the design decisions behind the scenes were anything but standard.

The prestressed concrete beams were designed within VDOT standards, including the use of 8000-psi lightweight concrete. However, the fully continuous design had to take into account special detailing for creep, shrinkage, and thermal effects; the detailing of the continuity diaphragms; the design and detailing of the 192 elastomeric bearings; stresses during shipping and handling; and the effects of camber.

One challenge was how to account for the creep, shrinkage, and thermal effects in this long, skewed, continuous (joints only at abutments) bridge. To understand the behavior of the bridge, a detailed analysis was performed using a combination of hand computations and finite element models (using LARSA-4D software) to better predict thermal centers and long-term creep and shrinkage behavior. The results showed total movement of approximately 6.75 in. at the abutment joints in the final condition. These results provided guidance for the design of the bearing system and for decisions about which substructure elements were to be fixed or expansion. After reviewing bearing types, reinforced elastomeric bearings were selected as the most economical choice. They were designed to be fully fixed at the three middle piers, with the remaining pier bearings designed as expansion bearings using sliding plates over elastomeric pads. To account for the transverse and longitudinal movements, the interior four beam lines used anchor bolts guided with elongated slots in the sole plates, whereas the exterior two beam lines of each side used sliding bearings without any anchor bolts. This concept allows the bridge to expand and contract as specified by the American Association of State and Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*,[1] while still providing positive connection through a combination of the anchor bolts and dowels at the fixed continuity diaphragms.

The long spans in this structure are connected by concrete continuity diaphragms that were designed to accommodate the differential temperature deformations in the superstructure cross section along with composite dead-load and live-load moments. To account for positive moments at the continuity diaphragms due to differential thermal gradients, the continuity diaphragms were designed based on research sponsored by the Virginia Transportation Research Council.[2] Based on this design methodology, additional bottom-flange continuity reinforcing steel was combined with bent-up strands to provide a more durable and resilient connection.

Experience, a review of available research, and a review of the assumed travel route to the project site indicated that stability and stresses during shipping and handling were significant concerns for prestressed concrete beams of the length and depth specified for this project. The bridge design engineer performed design checks for the lifting, handling, and shipping stresses for the long prestressed concrete beams using guidance from VDOT and a draft (at the time of design) of PCI's *Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders*.[3] Notes were added to the plans to inform the contractor about the design assumptions that were used.

In addition to the shipping and handling stresses, there were also concerns about how to account for camber in the long-span prestressed concrete beams. Recent research into camber prediction showed that if a time-dependent method were used for this analysis, it would provide a better prediction of the final cambers.[4–6] After the project was awarded, the contractor and fabricator worked directly with the design engineer to estimate the predicted camber of the beams based on the age of the beam at the time of erection according to the proposed project schedule. The contractor provided the beam production schedule along with the erection schedule, allowing

View of a typical pier near the middle of the bridge showing prestressed concrete beams before deck placement. The 12-span structure has 11 five-column concrete piers that reach up to 40 ft tall. The piers are supported by 520 plumb 16-in.-square prestressed concrete piles totaling over 27,000 linear feet. Photo: Whitman, Requardt & Associates.

Dual crane setting operation for the 85-in.-deep, 156-ft 2-in.-long prestressed lightweight concrete bulb-tee beams spanning over the CSX Transportation railroad. Clips on the beam web were for crossframes and utility hangers for conduits.. Photo: Whitman, Requardt & Associates.

the designer to provide adjusted pier and abutment seat elevations as a construction revision. While all beams had to meet a minimum of 90 days of age before the continuity diaphragm was placed, some beams were not scheduled to be erected until almost a year after casting.

The planning and collaboration among the designer, contractor, and fabricator were beneficial to the successful installation of the prestressed lightweight concrete beams and, ultimately, the reinforced concrete deck. The recalculated cambers based on the time-dependent method were used to adjust the beam seat elevations and predicted the actual cambers well enough to avoid any areas of deck thinning throughout the bridge.

Durability and Resiliency Considerations

The Atkinson Boulevard Bridge is the largest bridge in overall deck area in the city's inventory, over 70% larger than the next largest bridge. Therefore, durability of materials and the extensive use of jointless detailing were critical to provide a low-maintenance and resilient bridge structure. The superstructure materials were chosen to increase the durability of the bridge, and, following VDOT guidance, a combination of approved corrosion-resistant reinforcing steels were selected. VDOT Class I (low-carbon chromium) reinforcement was used in the substructure and prestressed concrete beams (for reinforcement that projects out of the beam) and VDOT Class III (stainless steel) reinforcement was used in the concrete deck.

View of 155-ft-long, 85-in.-deep prestressed concrete bulb-tee beams during the setting operation. Beam camber was a major concern due to the long times between beam production and erection. This concern was mitigated using time-dependent methods to recalculate the predicted camber and adjust the substructure seat elevations. As a result of the contractor and fabricator working directly with the design engineer, the camber predictions were a good estimate of the actual field-measured camber. Photo: Whitman, Requardt & Associates.

Conclusion

The decision to use concrete for the entire project provided the City of Newport News with a long-service-life, low-maintenance bridge. The use of lightweight concrete reduced both pile lengths and the total number of piles required. In addition, lightweight concrete also helped advance the design of the prestressed concrete beams by reducing the number of strands, which helped control camber growth. Lightweight concrete was the go-to option given these design benefits coupled with increased durability at minimal additional cost.

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PROJECT

Rapidly Restoring a Vital Transportation Route in Nebraska

by Ross Barron, Olsson

A rare bomb cyclone that hit Nebraska on March 12, 2019, caused the failure of the Spencer Dam in north-central Nebraska. The resulting flood damaged the existing U.S. Highway 281 bridge over the Niobrara River and created a new channel of the river that destroyed 1000 ft of pavement south of the bridge. Until a temporary bridge was installed, users had to endure a two-hour detour.

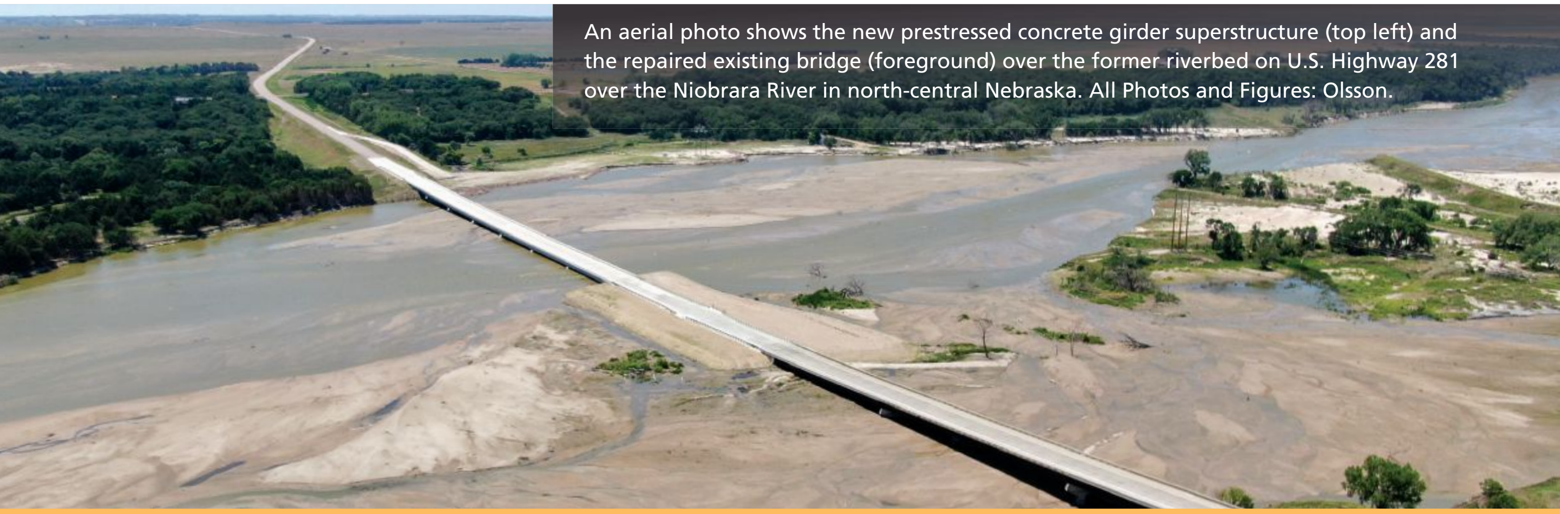
Weather experts called it a perfect storm but, in reality, there was nothing perfect about the weather events that hit Nebraska with a wallop never before seen in the Cornhusker State.

On March 12, 2019, the state was hit by a rare bomb cyclone, which is a storm caused by a steep drop in barometric pressure. The results were blizzard conditions in the west, heavy rains in the east, and Category 3 (111 to 129 mph) hurricane-force winds throughout the state.

What made this storm unique was not so much the amount of moisture as the timing. Nebraska was coming out of a severe winter with heavy snow and colder-than-normal temperatures that had frozen the soil to a depth greater than 1 ft in the weeks leading up to the storm, and creeks and rivers were iced over. When the rain hit the eastern part of the state, nothing could slow a massive runoff of up to 3 in. of rain and rapidly melting snow.

Widespread Damage and Destruction

As a result of this bomb cyclone, several major drainages in central and eastern Nebraska flooded simultaneously, causing levees to fail throughout the state. Nearly 200 miles of highway, 30 state bridges, and a plethora of county roads were either damaged or destroyed. One of the damaged roadways spanned the Niobrara River on U.S. Highway 281 (U.S. 281) in north-central Nebraska. Massive ice floes in the Niobrara River to the west of an existing bridge resulted in failure of the Spencer Dam, which



An aerial photo shows the new prestressed concrete girder superstructure (top left) and the repaired existing bridge (foreground) over the former riverbed on U.S. Highway 281 over the Niobrara River in north-central Nebraska. All Photos and Figures: Olsson.

profile

HIGHWAY 281 OVER THE NIOBRARA RIVER EMERGENCY RESPONSE / BOYD AND HOLT COUNTIES, NEBRASKA

BRIDGE DESIGN ENGINEER: Olsson, Lincoln, Neb.

PRIME CONTRACTOR: Hawkins Construction Company, Omaha, Neb.

PRECASTER: Concrete Industries, Lincoln, Neb.—a PCI-certified producer

OTHER MATERIAL SUPPLIER: Temporary prefabricated modular bridge supplier: ACROW Bridge, Parsippany, N.J.

A view of the skewed ends of the NU1800 prestressed concrete girders at an abutment. This photo was taken before the semi-integral abutment turndown placement and before the deck forming and concrete placement. This bridge featured a jointless deck system across the length of the structure. Expansion joints were placed at the end of the approach slabs, which were founded on pile-supported grade beams placed 20 ft beyond the abutments.

subsequently and dramatically created a brand-new path for the Niobrara River. The flooding left a wide path of destruction, including damage to the existing bridge and 1000 ft of pavement at the south end of the bridge.

The damaged pavement and bridge affected residents of Boyd and Holt counties in big ways. Because the bridge was out, two-hour driving detours to work, school, medical care, and other important resources were the norm. Something had to be done to help those affected—and fast.

An engineering and design firm was tapped to evaluate the damage, develop a solution that would restore highway traffic quickly, and design a new connection across the new river alignment. The design team understood the challenge at hand and that time was of the essence.

Early in the project, it became clear that the Nebraska Department of Transportation would have to bid the repair of the existing bridge, construction of a temporary roadway and bridge, and construction of the permanent roadway and bridge all together. A design project this massive would typically take a year or more to get ready to bid.

How difficult was this task? First came the realization that to restore traffic for this essential highway route in just four months meant setting an internal deadline of April 17, 2019, to complete design work for bidding. That gave the engineering design team four weeks to design two bridges—one temporary, one permanent. It took the efforts of technical experts across the firm to quickly mobilize, coordinate, and get to work. Everyone on the team knew that these were not ordinary circumstances and took to heart the mission at hand.

When teammates traveled to the site to better understand the engineering challenge, they witnessed the utter devastation of the landscape. The river was still raging because of very high flows, and the edges of the river were unstable and continuing to erode

Girders are set and are being prepared for concrete deck placement on the U.S. Highway 281 Bridge over the Niobrara River. This photo is taken from the south bridge abutment looking along the bridge span over the new river channel. A temporary crossing for contractor access was constructed adjacent to the permanent bridge to allow cranes to access the jobsite and place girders. Multiple cranes were on site during construction, and space was generally limited between the temporary bridge and the permanent bridge.

NEBRASKA DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: A 1050-ft-long, seven-span, continuous, prestressed concrete I-girder bridge

STRUCTURAL COMPONENTS: Thirty-five NU1800 precast prestressed concrete I-girders with an 8-in.-thick, cast-in-place concrete deck; cast-in-place concrete substructure units on driven-pile foundations

CONSTRUCTION COST: $26.5 million

AWARDS: American Council of Engineering Consultants (ACEC) Nebraska 2020 Grand Award Winner, ACEC 2021 National Recognition Award

Looking along the NU1800 precast, prestressed concrete girders toward one of the permanent bridge piers.

quickly. The design team quickly made an accurate aerial topographic survey so that the engineers could get to work.

With aerial photography and site geotechnical sampling, experts in fluvial geomorphology and hydrology provided invaluable insights into the Niobrara River's new path and how it would continue to evolve over time. These experts furnished recommendations for temporary and final construction that accounted for the long-term behavior of the new river alignment. Recommendations included designing the new bridge to span nearly the entire width of the new channel, which would be more cost effective and would allow the new channel to naturally adjust as necessary within the reach.

The channel elevations were expected to be high during construction but to decrease over time, so pier and pile caps were designed for the lower long-term elevations and 10 ft or more of excavation was required. Several bank stabilization and flow deflection alternatives were evaluated for erosion control, but because of environmental concerns and regulatory restrictions, an off-channel countermeasure was needed. Therefore, workers constructed a buried sheet-pile wall set back from the river bank to prevent erosion from extending beyond that point. In addition, long-term monitoring was recommended to identify and assess any issues related to the combination of predicted sedimentation within and upstream of the bridge reach and winter ice formation and jams.

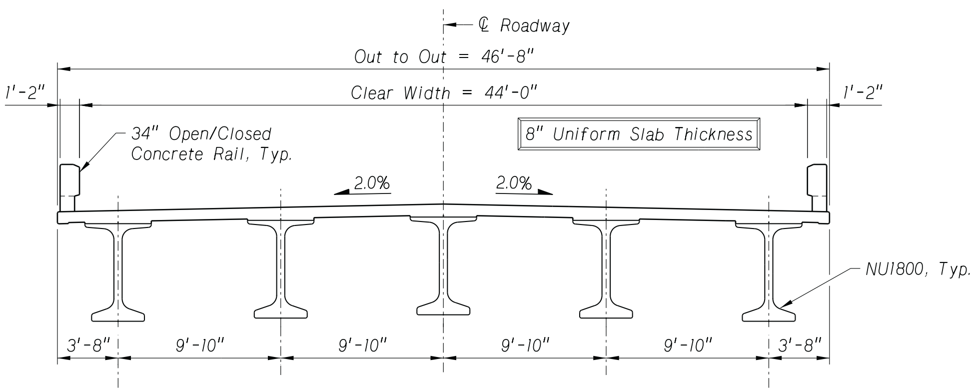
Temporary Bridge

The bridge engineers worked to develop a temporary bridge across the new river alignment that could be deployed as quickly as possible. The Nebraska Department of Transportation helped find available modular prefabricated bridge manufacturers to help on multiple projects throughout the state. The design team coordinated with suppliers early in the design phase and developed a partnership with a company that was dedicated to quickly providing materials to support the state in its efforts to restore the highway system across Nebraska. The results of the hydraulic and structural alternative analysis led to the design of a six-span, 600-ft-long modular bridge within the limits of a relatively stable portion of the new river channel. This temporary bridge was intended to be the in-service detour route for more than a year, so the engineers needed to consider how the river conditions might shift or evolve seasonally during that time. Temporary roadway connections on each end of the bridge were made using a significant amount of rock riprap to stabilize the sand base of the riverbed. The temporary bridge was designed, bid, and constructed rapidly, and highway traffic was restored just four months after the flooding disaster.

Concurrently with the development of a temporary bridge and roadway solution, the design team was also hard at work providing the design for repair of the existing bridge and the permanent solution for the new river crossing. Following the dam failure, the existing bridge was damaged by an 11-ft wall of ice chunks the size of trucks. Luckily, simple repairs allowed the contractor to quickly restore the structural viability of that bridge.

Permanent Bridge

The permanent bridge design crossing the new river channel was not a simple task. The hydraulic analysis considered the current and future conditions of the new river channel, including the potential for the braided channel to shift significantly over time, and showed that a 1050-ft-long bridge would be necessary to span the new river channel. For economy, simplicity, and durability reasons, a prestressed concrete girder superstructure was selected as optimal for the site. A seven-span bridge using NU1800 girders made continuous for live



Typical cross section of the new bridge. The girder design required fifty 0.6-in.-diameter strands and a design concrete compressive strength of 10 ksi.

Aerial view of the new bridge location from the south abutment, with the existing bridge in the background. The hydraulic analysis and bridge design considered the current and future conditions of the new river channel, including the potential for the braided channel to shift and the channel bottom to lower significantly over time. The new bridge was constructed on the original alignment to the right of the temporary work bridge, which was also used to construct the temporary modular bridge used to restore traffic.

load with a 20-degree skew with respect to the girders and consisting of 155-ft central spans and 140-ft end spans was determined to be structurally and hydraulically optimal. The bridge was jointless across the length, with expansion joints provided at a pile-supported grade beam at each end of the approach.

The girder design required fifty 0.6-in.-diameter strands and a design concrete compressive strength of 10 ksi.

The project encountered fabrication challenges that were mostly centered around availability. Girders were being cast for bridges across the state, and the girder fabrication timeline drove the construction schedule. Erection required a temporary crossing between the permanent and temporary bridges to enable the contractor to deliver and place the girders.

One of the key challenges for designing the permanent bridge was developing an understanding of how the new channel of the Niobrara River would evolve over time and the role the flow-line elevation and scour would play in the stability of the bridge foundation. The failure of the dam upstream would lead to aggradation for a time. Judging from the upstream and downstream conditions, it was clear the channel would eventually normalize to a bottom-of-channel elevation well below the postflood condition. Because of contractor availability and the expediency of the project, it was determined that driven-pile foundations constructed with cofferdams would be more economical than drilled-shaft construction and would aid in the constructability of the project. Although challenging to deploy in the evolving river conditions, this approach provided for a structure that could endure channel conditions that were expected to vary dramatically between the bridge's short-term and the long-term service lives.

The approach used to address the project requirements worked well. The engineer met the April 17 deadline for the design of the project, and the estimated project cost for the temporary and permanent bridges, the associated roadway, and the repairs to the existing highway bridge closely matched the awarded bid. Considering the devastation across the state, designing, bidding, and constructing the project quickly was of paramount importance. The contractor that was awarded the project became a close partner with the design team to maximize efficiency on the project, and crews worked long hours to permanently restore the highway.

How daunting was this project? The engineer's technical leader said he had never seen anything like it in his more than 25 years in the profession.

A Feat of Engineering

The temporary bridge opened on July 26, 2019, a week ahead of schedule, providing a vital route for local residents. Restoring the major transportation route was essential to the economy of north-central Nebraska. The bridge closure had forced some motorists to take detours as long as 127 miles, adding two hours to necessary trips that formerly took only minutes, according to Derek Bentz, chair of the village board in nearby Spencer.

Restoring the traffic across the river in fewer than four months required extraordinary coordination and a lot of hard work. This project truly demonstrated the importance of engineers within our community. At the celebration of the opening of the new bridge in October 2020, Nebraska governor Pete Ricketts said of the $26.5 million project "It was an incredible feat of engineering and construction that everybody came together to make this happen. It really has been a testament to the partnerships in our state."

Ross Barron is a lead engineer for the Nebraska Roads and Bridges team at Olsson in Lincoln, Neb.

Repair and Maintenance of Post-Tensioned Bridges: An NCHRP Synthesis Report

by Dr. Natassia Brenkus, Ohio State University

Post-tensioned (PT) bridge construction provides a durable, economical means of spanning long distances. Coordinated efforts by the industry and stakeholders have greatly improved the durability of these structures since the technology's introduction in the United States. While most states have PT bridge structures, the way these bridges are designed, repaired, inspected, and maintained remains nonuniform. National Cooperative Highway Research Program (NCHRP) Synthesis 562[1] assembles valuable information about the repair and maintenance of PT concrete bridges, making it available to the entire highway community. This effort collates the most recent PT bridge repair and maintenance experiences and includes a literature review, a survey of state departments of transportation (DOTs), and five case studies from around the country.

In 2010 an inspector noted light penetrating the interior box of the Plymouth Avenue Bridge in Minneapolis, Minn. The inspection findings prompted further investigation and rehabilitation plans. All Photos: Corven Engineering, a Hardesty and Hanover company.

State of Post-Tensioning Practices

Post-tensioning made its way to the United States in the early 1950s with the Walnut Lane Bridge in Philadelphia, Pa. Soon after that, the first PT bridge in Florida—the Sunshine Skyway Bridge in Tampa—was constructed in 1954. Although PT concrete is a durable construction method, some aspects present inherently difficult repair and maintenance situations. Most notably, the grout used to encapsulate a post-tensioning tendon's prestressing strands creates a difficult-to-inspect scenario. The geometry and heavy reinforcement in anchorage regions and deviation blocks also make it difficult to inspect tendons in these areas.

Several incidents in the early 2000s instigated improvements in the industry, ranging from the publication of guidance documents to the development of certification programs for post-tensioning personnel (for details, see articles in the Winter 2017 and Summer 2019 issues of *ASPIRE*®). Because construction practices and the quality of cementitious grout commonly used in bridge tendons have been identified as significant contributors to tendon damage, significant efforts have been made to improve them. Many efforts were undertaken to address grout issues of that era, including concerns about poor grout quality, incomplete filling of tendons, grout contamination, and underweight bags. Additional improvement to corrosion-protection systems for PT structures came with the switch from metal to plastic ducts, and the introduction of superior duct-splicing details.

The industry continues to evolve in response to stakeholders' concerns. The introduction of prebagged thixotropic grouts was one innovation aimed at improving the durability of PT structures; however, grout deficiencies have not been completely resolved. Newer grouts have also demonstrated the potential for grout segregation, soft grout, excessive bleed water, and high chloride and sulfate contents when the latest specifications and procedures are not followed.[2] Additional approaches have been undertaken to improve the overall serviceability and durability of PT bridges, including the use of redundant tendons, flexible filler materials for new tendons, proprietary impregnation materials for grouted tendon repair, and surface seal coatings of the main concrete section.[3]

Improvements to PT structure durability are due in part to the post-tensioning community's development of consensus documents, certification programs, and research efforts. Taken as a whole, these investments in both standardizing and advancing the technology have gone a long way in improving the state of the practice. However, implementation by state DOTs remains fragmented and inconsistent.

Survey

As part of the NCHRP synthesis, state DOTs were surveyed about their experiences with PT bridge structures, including detailed aspects related to design, construction, maintenance, and repair. (Survey responses can be downloaded from http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_562Answers.pdf.) There are thousands of PT structures in state bridge inventories; nearly every state DOT (44, to be exact) reported having PT structures, with a wide variety of structure types represented. States without PT structures cited lack of familiarity, concerns regarding durability and quality, lack of need, and lack of local industry presence as reasons they do not have such structures.

The Plymouth Avenue Bridge in Minneapolis, Minn., is coated with surface seal for enhanced protection after repairs.

Most state DOTs have updated their post-tensioning specifications within the past seven years, and many refer to two consensus documents from the Post-Tensioning Institute (PTI) and the American Segmental Bridge Institute (ASBI) for best practices: PTI/ASBI M50.3, *Specification for Multistrand and Grouted Post-Tensioning*[4] and PTI M55.1, *Specification for Grouting of Post-Tensioned Structures*.[5] Lessons learned since the grout problems uncovered in the early 2000s are generally, but not universally, reflected in DOTs' guidance for PT bridge construction. A notable number of state DOTs model their post-tensioning installation practices on the PTI documents or other states' specifications, but inconsistency still remains among many states. Additional efforts to ensure nationwide awareness of improved practices for PT construction may be warranted.

According to the survey, 23 state DOTs have experience with repair to their PT structures. DOTs reported that many of their repair actions occur during construction and are performed on problematic construction details such as duct splices, anchorage pour backs, confinement reinforcement, and other geometry conflicts. DOTs also reported that they still have issues with the injection process, including grouting, air pressure tests, and vacuum procedures, and they emphasized the importance of personnel training and experience. Repairs are still periodically performed to address grout deficiencies associated with the pre-2000 materials and procedures. Other causes of damage leading to repair are not specific to PT structures, such as vehicle impact, poorly designed drainage systems, poor concrete quality, and defective waterproofing membranes.

State DOT interest in innovative approaches to repairing and maintaining PT structures is high. Many agencies have used fiber-reinforced polymers and proprietary corrosion inhibitors in their repairs, and interest in these materials is increasing. Innovative approaches for internal tendon remediation, including the use of drying techniques and impregnation products, are under investigation.[6] Though most states rely on visual inspection for their PT structures, many states have investigated the use of nondestructive technologies to enhance the ability to assess the condition of grouted tendons.

Case Studies

NCHRP Synthesis 562 presents five case studies of PT bridges and their repair and maintenance actions. The cases were chosen to represent different geographic areas: Florida, South Carolina, Ohio, Virginia, and Minnesota. One thing some of the case studies have in common is a lack of post-tensioning-specific knowledge held by persons performing the routine inspections of these structures. In some instances, evidence of damage to the PT system was not identified until the damage became critical. Just as the implementation of certification programs has gone a long way toward improving the construction of PT structures, the education of inspectors and other personnel engaged in the repair and maintenance of PT structures is imperative for improving in-service performance.

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The Plymouth Avenue Bridge's failed drainage system allowed water from the deck passing through pipes in the post-tensioned box girder to be a source of moisture intrusion for many years. Remediation included tendon replacement, re-entombment of exposed tendons, repair of pour backs, crack injection, and removal of the original drainage system.

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Detailing Segmental Concrete Box Girders for Constructability – Part 2

by Jeremy Johannesen, McNary Bergeron & Associates

The Great Baltimore Fire of 1904 is a historic example of the need for standardization. At the time, 600 different hose-coupling devices were in use in the United States. Crews responded from as far away as New York, only to find that they were unable to connect their hoses to the hydrants due to the incompatible couplings. Decades later, the United States' engineer-president, Herbert Hoover, pushed for the standardization of screw threads, which was ultimately so successful that we can now assume that threaded fasteners made on opposite sides of the country will fit together.

Although concrete construction is infinitely adaptable, standardization is still key to both the economics and quality of a project. In construction, standardization can be summed up as doing more, thinking less—at least on site or during production. This article summarizes a number of considerations that are specific to segmental bridge construction but also applicable to other types of construction.

Concrete Geometry

The principles for segment geometry are commonly accepted and understood within the industry. Geometry in curved alignments is achieved by chording the individual segments. In plan view, segment joints are perpendicular to the chord of the segment being cast. In profile,

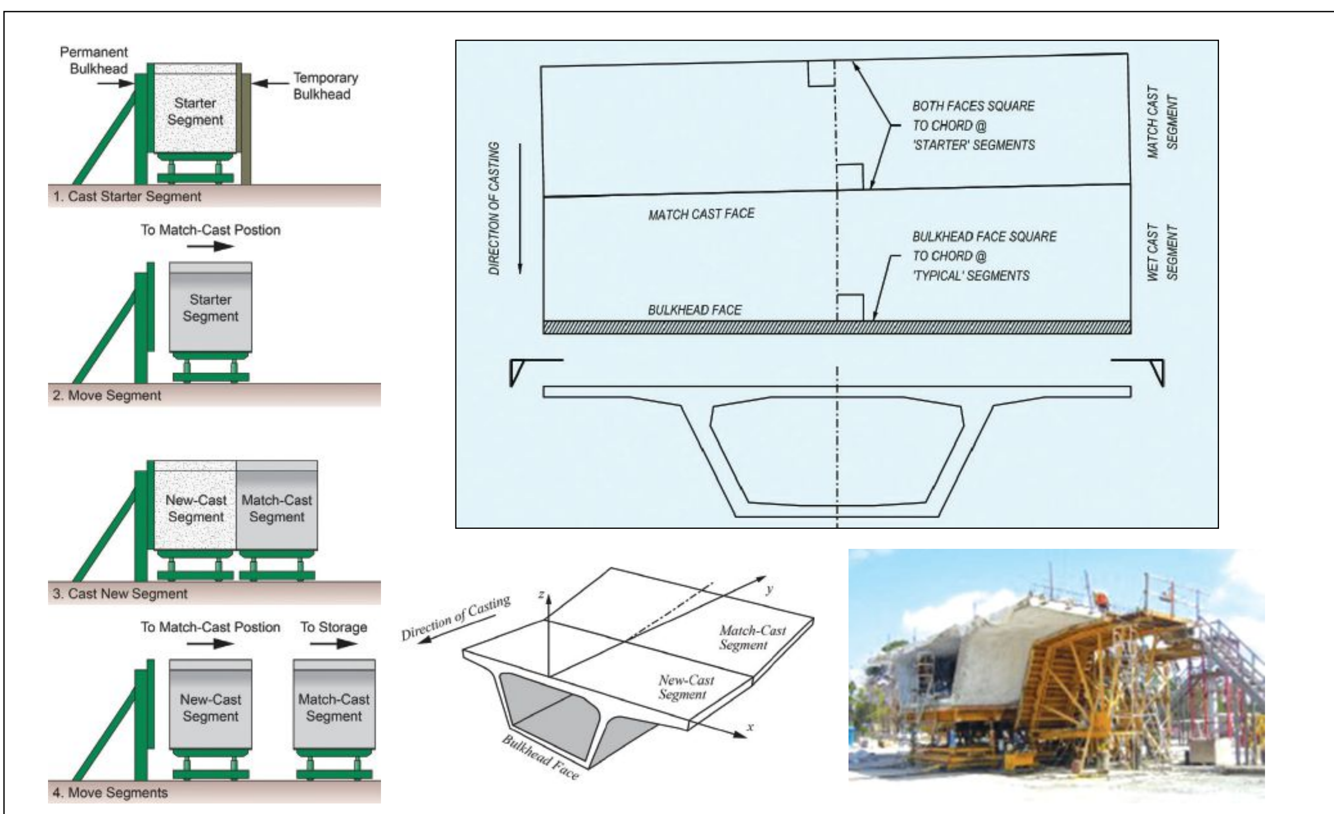

Figure 1. The schematic of the short-line casting sequence (left) shows how the starter segment is moved to the match-cast position and is oriented based on the needed geometry. The new segment is cast the next day. When it reaches its strength, the match-cast segment is moved to storage, the new-cast segment takes its place as the match-cast segment, and so forth. Geometry on a curved alignment is accommodated as shown on the right. The segment made in the new-cast position is flat or straight along the vertical axis with regard to the bulkhead. The relative geometry is achieved through the manipulation of the match-cast side, which was the segment cast the day before. Figure: PCI (left) and McNary Bergeron & Associates (right).

joints are vertical at the time of casting (**Fig. 1**).

While it is understood that this process provides a basis for survey control, the process is primarily based on the practical limitations of the formwork system. In very general terms, variability is limited to the match-cast face, or open end of the form.

Design should be based on an understanding of the formwork system, and simplicity should be the goal. To be specific:

- Avoid variations in cross-section thickness, especially within a casting unit.
- Use consistent anchor-block geometry to avoid formwork modifications during the casting cycle.
- Avoid using top-slab anchor blocks, as these significantly complicate the core form design and operation.
- In precast segmental concrete, avoid variations in section depth.
- In cast-in-place segmental concrete, the longer segment length and formwork related to deviator ribs for external tendons pose a construction challenge. Casting the rib as a secondary pour simplifies the formwork and removes nonstandard details from the critical path.

Post-Tensioning Duct Layout

Segmental formwork inherently requires a fairly standard layout. To keep details simple and consistent, consider the following:

- Set the cantilever (top longitudinal) tendon anchorage low enough such that the spiral clears the first transverse tendon (**Fig. 2**).
- In variable-depth structures, index the bottom-slab tendon layout and anchor-block geometry from the inside corner of the box girder. With this approach, the relative geometry between the anchor block and the ducts remains consistent as the depth of the girder varies (**Fig. 3**).
- Use "tight radius" ducts where needed but avoid bends that require custom-bent steel pipes (spelled "pipe$"). Designing with radii that can be achieved using corrugated plastic duct should be the goal for cost-effective design.
- Consider the duct radius in the plane of the bend. It is not possible to bend a duct to different radii in both plan and elevation.

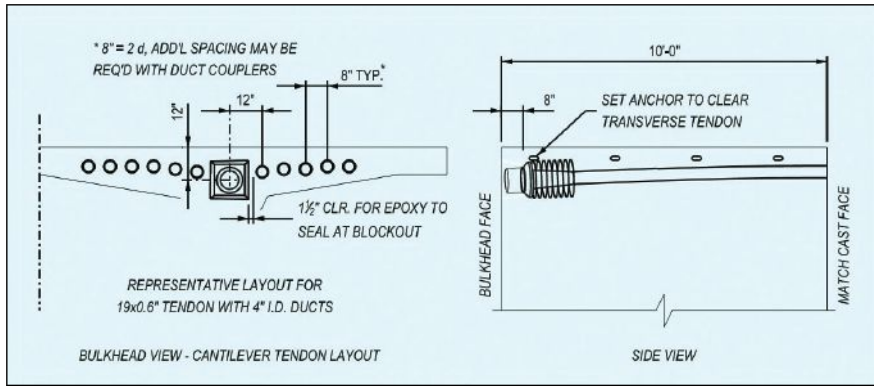

Figure 2. The cantilever (longitudinal) tendon anchorage should be set low enough such that the spiral clears the first transverse tendon. Figure: McNary Bergeron & Associates.

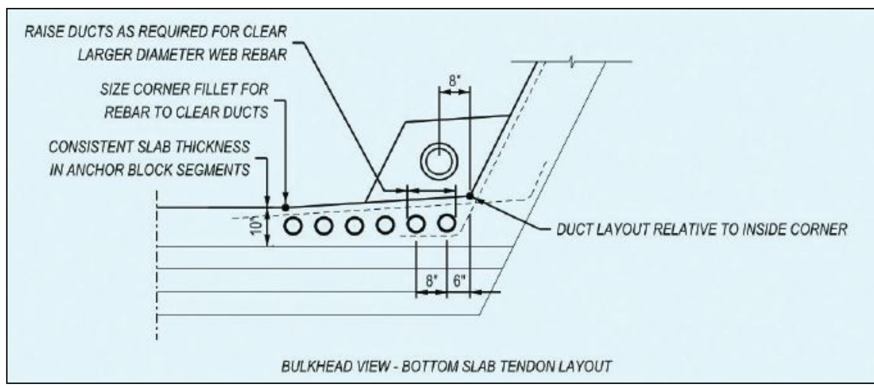

Figure 3. Avoid variations in bottom-slab thickness among segments within a casting unit, and index the bottom-slab tendon layout and anchor-block geometry from the inside corner of the box girder. With this approach, the relative geometry between the anchor block and the ducts remains consistent as the depth of the girder varies. Figure: McNary Bergeron & Associates.

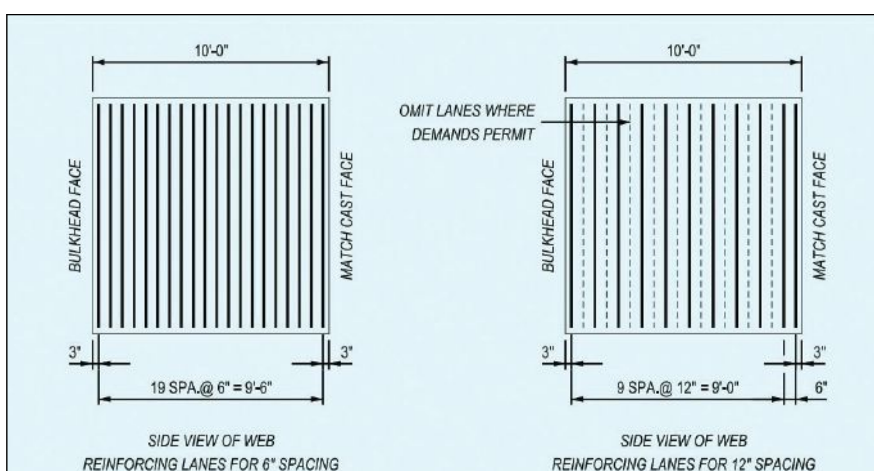

Figure 4. Use reinforcing bar spacings with a common denominator, such as 6 in. and 12 in., to simplify the reinforcement layout and improve efficiency. Figure: McNary Bergeron & Associates.

- Use diabolos for external post-tensioning (PT) to allow standard placement for a range of tendon profiles. Diabolos without stay-in-place plastic formers require additional spacing to ensure clear cover between the reinforcement and the formed hole.

Reinforcement Layout

Many people in the field assume that reinforcing bars should simply be spaced equally over any face of concrete; however, this approach does not lend itself to integration of other items. One simple method to integrate details is to adopt an assumed reinforcement layout early in the design. This creates dedicated reinforcing lanes, and everything else can be integrated outside of the lanes. Drainage, lighting, construction embeds, and even PT can go anywhere as long as they go between the reinforcing bars.

When spacing reinforcement, use common denominators. For example, integrating reinforcing bars with 8 in. spacing with bars spaced at 6 in. will either result in 6 in. spacing with some random gaps, or 8 in. spacing with random bundles. Using spacings with a common denominator, such as 6 in. and 12 in., resolves this problem (**Fig. 4**). Similarly, using obscure spacing invites mistakes. Stick to whole inches or centimeters, which can be easily read on a dirty tape measure.

When segments are rectangular, reinforcing bar layout is simple (offset the first bar half of the nominal spacing from the bulkhead face and then repeat at the nominal spacing). When segments have a skewed face, space the bars parallel to the bulkhead (the square end) from the bulkhead to beyond the anchor block reinforcement or other details requiring integration. Then, vary the spacing in an accordion fashion for a limited length near the skewed face (**Fig. 5**).

This approach is similar to timber framing, where rather than spacing the studs uniformly along each wall, the studs are spaced at 16 in. and any remainder is left as a single, short spacing. This is a well-understood technique that does not require integrated shop drawings. Furthermore, it is inherently compatible with different building components. For example, a 4 × 8 ft sheet of plywood is multiples of 16 in.; thus, the sheeting aligns with the framing studs.

While positioning of PT generally has priority over positioning of reinforcing bars, it is worthwhile to detail the transverse tendons between the lanes of reinforcing bars (**Fig. 6**). This is baseball's "hit 'em where they ain't" strategy applied to detailing. Conversely, locating transverse tendons without regard for the reinforcement results in nonuniform reinforcing bar spacings and, sometimes, the need for additional reinforcement to cover the resulting gaps. Addressing these issues requires extra labor.

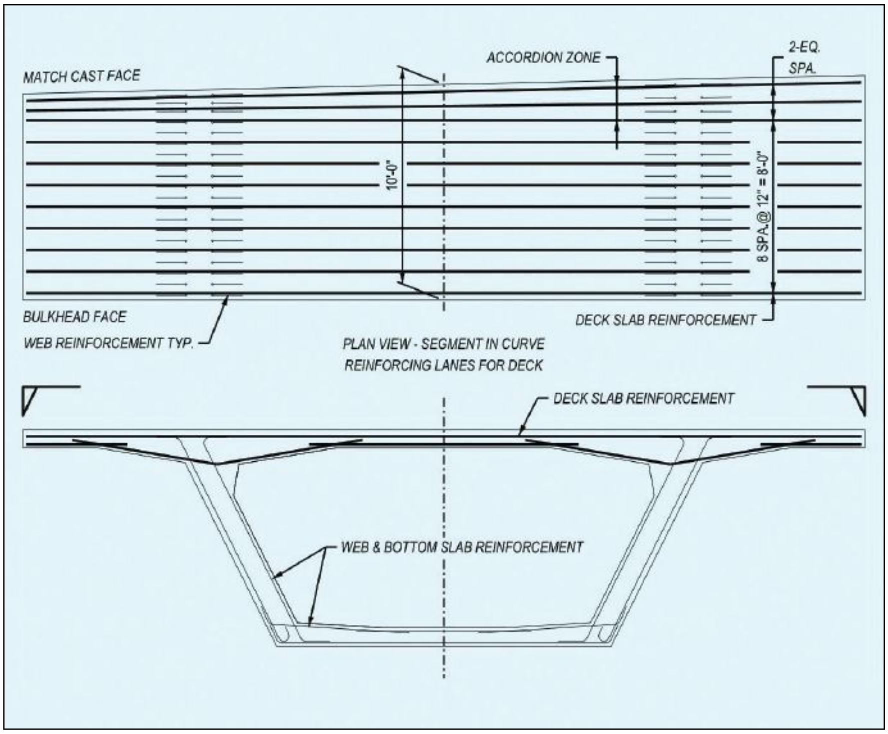

Figure 5. Adopt a reinforcement layout early in the design, and create dedicated lanes of reinforcing bars with spacings of common multiples. When segments have a skewed face, space the bars parallel to the bulkhead (the square end) from the bulkhead to beyond the anchor block reinforcement or other details requiring integration. Then, vary the spacing in an accordion fashion for a limited length near the skewed face. Web and bottom slab reinforcement would be placed using the same approach. Figure: McNary Bergeron & Associates.

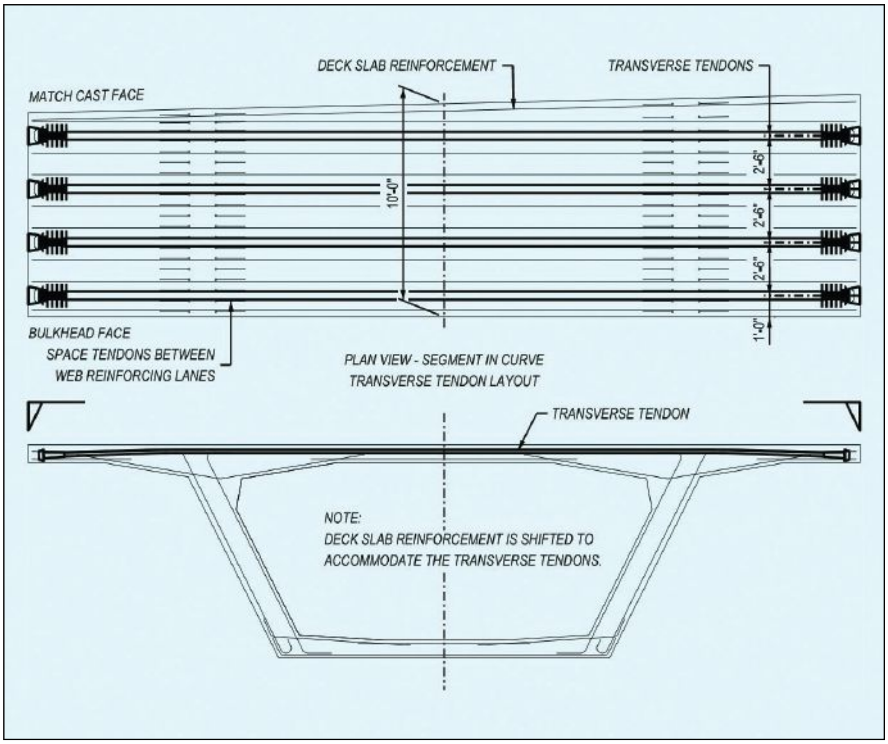

Figure 6. Detail the transverse post-tensioning tendons between the lanes of reinforcing bars. Locating transverse tendons without regard for the reinforcement results in nonuniform reinforcing bar spacings, and additional reinforcement is sometimes needed to cover the resulting gaps; this work requires additional labor. Figure: McNary Bergeron & Associates.

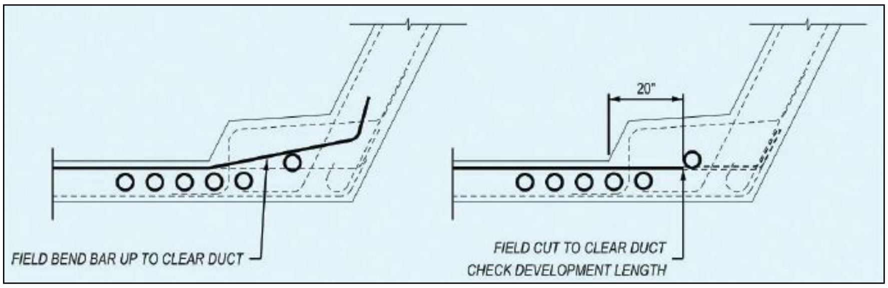

Figure 7. Tendon paths must not be altered to snake through the reinforcement. Where tendons pass through reinforcing mats, a detail should be part of the design. Two options are shown here. Pass-through details like these should be part of the design. Figure: McNary Bergeron & Associates.

Reinforcement at Tendon Anchorages

The anchor blocks' reinforcement must be considered in combination with the actual tendon geometry, so that the reinforcing bars are located in the open lanes between the ducts. Tendon paths must not be altered to snake through the reinforcement.

It is important to slope the inside face of the anchor blocks. By varying the clear cover, the outer block reinforcement may be detailed to follow either straight or deviating tendon paths.

Where tendons pass through reinforcing steel mats, the design should specify how. Shifting reinforcement longitudinally to clear the conflict is not always practical because it displaces too many bars and leaves a large gap. Make the pass-through detail part of the design (**Fig. 7**).

For PT or any large item crossing a plane of reinforcing bars, there is a strong case to be made for field-cutting the "typical" reinforcing cage and adding bars to compensate for the cut bars using a specified detail. This allows crews to focus on production rather than trying to figure out which bars in a group are different from the rest.

Conclusion

This article is a companion to "Detailing Segmental Concrete Box Girders for Constructability," published in the Summer 2021 issue of *ASPIRE*®, and it is intended to provide "lessons learned" from several generations of experience. This includes cases where every segment on the project is cast using a single, already existing, no-frills form. These examples of standardization show that segmental construction can be an economical option. I hope you find these tips useful and I hope they spark some new ideas.

Jeremy Johannesen is a principal with McNary Bergeron & Associates in Broomfield, Colo.

EDITOR'S NOTE

PCI offers free eLearning modules on many transportation topics—including geometry of straight and curved bridges—that can enhance engineers' detailing and constructability knowledge. See page 27 of the Summer 2021 issue of ASPIRE® *for additional information and a sampling of course options.*

Embedded Inserts Add Up to Big Savings on Minneapolis Bridge

by Doug Knapp, BrandSafway

Figure 1. View of spans 3 to 6 of the Tenth Avenue Bridge in Minneapolis, Minn., looking north. Suspended platforms were used as debris shields on span 4 and for work access on span 5. Photo: Doug Knapp.

Constructed in 1929 and listed on the National Register of Historic Places, the Tenth Avenue Bridge in Minneapolis, Minn., features seven iconic arches (**Fig. 1**). Designed by noted Norwegian-American engineer Kristoffer Olsen Oustad, it is typical of the reinforced concrete bridges built in Minneapolis–St. Paul in the early 20th century to span the high Mississippi River bluffs.

Today, the bridge should also be known for its use of embedded concrete inserts (**Fig. 2** and **3**) to provide a connection point for suspended work platforms. Such platforms are currently being used for the bridge rehabilitation, and they may also be used for future maintenance or bridge inspections, a concern that bridge owners are now being encouraged to consider in design. Concrete embeds are not new; however, using embeds for attaching a proprietary rotating-suspension-point (RSP) assembly is. In 2019, RSP assemblies proved their value for bridge renovation, construction, inspection, maintenance, and repair activities on a railway viaduct rehabilitation project (also a concrete arch) in Romania (**Fig. 4**).

Embedded inserts are used in the precast concrete industry for many applications: structural connections, securing handling hardware, anchoring formwork, or for pipe or other supports. For the Tenth Avenue Bridge, the embedded insert is a low-cost, proprietary item (available from several manufacturers) consisting of a 1¼-in.-diameter NC-threaded ferrule welded to struts, which are then welded to a coiled wire to create a shear cone for improved concrete tension and shear capacities (**Fig. 5**). The proprietary RSP assembly is secured to the NC-threaded embedment using a 1¼-in.-diameter all-thread rod (**Fig. 6**). The threaded rod material must be specified to meet the required loading criteria. The rotating assemblies on the Tenth Avenue Bridge will be removed after the project, but the embedded anchors will remain for future use when access is needed on the bridge for inspection, maintenance, repair, refurbishment, or fall arrest. It is recommended that anchors intended for reuse be plugged with a metal or plastic fastener when not in use to prevent corrosion or fouling.

Establishing the capacities of the concrete embed and all-thread rod can be challenging. Multiple uses require compliance with multiple codes.[1–4] For example, the factor of safety and loading criteria requirements for a construction work platform are different from those for a formwork connection, fall-arrest system, railing (permanent or temporary), or pipe support. Other factors that must be considered are concrete strength, insert capacities of a particular manufacturer, spacing of inserts, and edge distance. It is paramount that a licensed engineer design and specify the shear and tensile capacities and intended use of the embedded concrete inserts. These capacities and uses must be a part of project documentation (plans and specifications) and, in some cases, may require labeling per the applicable Occupational Safety and Health Administration standard.

In the spring of 2020, the City of Minneapolis initiated the restoration project on the Tenth Avenue Bridge, which included replacing the bridge deck and concrete railing, patching piers and arches, replacing and patching deteriorated beams and spandrel columns, and applying corrosion-prevention treatment of the arch ribs and a new surface finish.

The contractor initially asked BrandSafway to engineer the work platforms for spans 4 and 5 using their proprietary suspended access system. Because of the access system's load capacity, the contractor was able to simultaneously place up to 30 people working on multiple levels. As a result of this efficiency, the scope of the project was expanded to include access platforms for three additional spans.

Because of construction schedule constraints, the existing bridge deck remained in place on span 5. In this instance, holes were drilled through the deck to allow suspension chains to drop through. Because concrete for the new deck in spans 3 and 4 was placed before the arch repair, the contractor was able to install 320 concrete embeds without having to drill holes for post-installed anchors in the new deck or in the spandrel caps. After the deck was complete, the RSP assemblies were attached to threaded rods installed in the embedments. The RSP assemblies and threaded rods were removed after work was complete, but the embedded inserts remain in the underside of the bridge deck for future access needs.

Figure 2. Embedded concrete inserts (indicated with arrows) are secured to the deck slab reinforcement with wire ties before placement of the new Tenth Avenue Bridge deck. Photo: Doug Knapp.

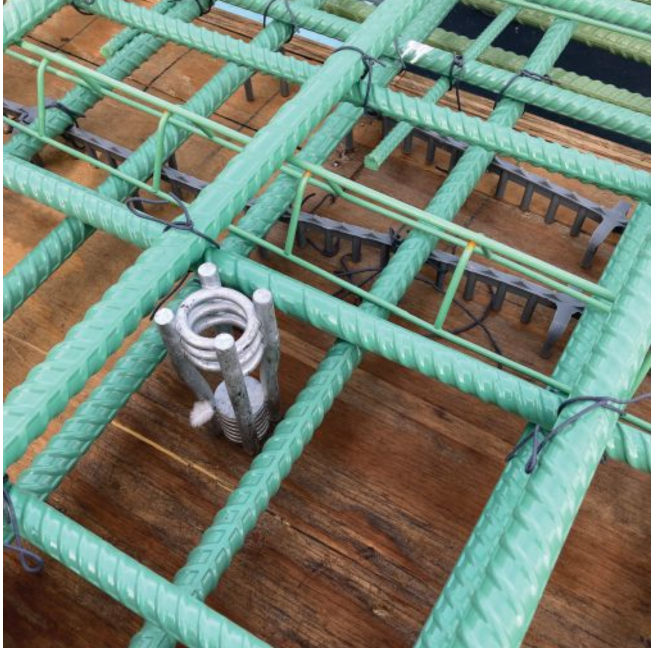

Figure 3. Using hundreds of embedded concrete inserts in the cast-in-place bridge deck eliminated hundreds of hours of labor to drill holes for post-installed anchors. Photo: Doug Knapp.

Figure 4. An innovative proprietary rotating-suspension-point assembly was used for the rehabilitation of the Caracău Viaduct in Romania. Photo: Doug Knapp.

Figure 5. Proprietary concrete ferrule inserts are available from several manufacturers. Consult the specific manufacturer for capacities and installation requirements. For the Tenth Avenue Bridge project, the insert was threaded for 1¼-in.-diameter NC threads and had four struts instead of the two shown in this representative photo. Photo: Dayton Superior.

The concrete embeds add a small amount to material costs, take only minutes to install, and avoid issues such as interference with reinforcement and certain elements of supervised installation and inspection required for post-installed anchors (see the four-part series on post-installed anchors that started in the Summer 2020 issue of *ASPIRE*®). In this situation, by eliminating the time to drill and patch holes (about an hour per hole), the use of 320 concrete embeds translated to a savings of about $250,000 for the project and accelerated the work schedule.

With the demonstrated advantages of the concrete embeds on this project, a similar solution is being implemented just seven blocks away on the Third Avenue Bridge, another iconic arched bridge.

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EDITOR'S NOTE

This article reports on a successful solution for the Tenth Avenue Bridge that also has potential use for future rehabilitation or maintenance activities. If and when the embedded inserts are reused, the condition of the embedded inserts and their available capacity should be confirmed before use.

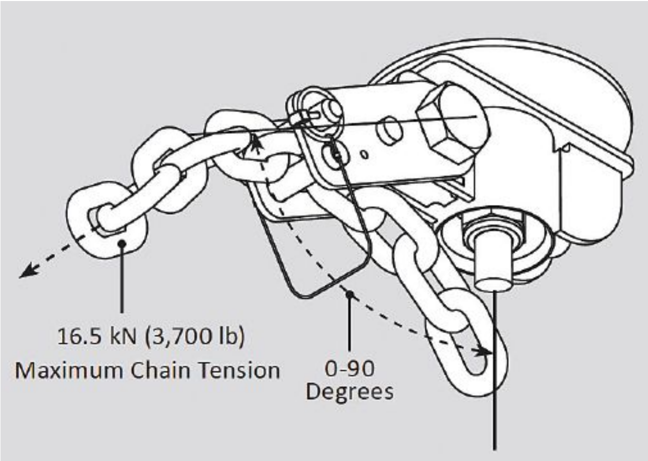


Figure 6. The design of this proprietary rotating-suspension-point assembly ensures the load pulls in a straight line. Each assembly is rated for 3700 lb. The capacities of the all-thread rod and the concrete insert are not part of the assembly and must be designed by a licensed engineer according to the appropriate codes. Figure: Doug Knapp.

Is Fly Ash Going Away?

by Dr. Tyler Ley and Dr. Marllon "Dan" Cook, Oklahoma State University

Fly ash has become a fundamental ingredient in concrete mixtures. It lowers the cost, improves the durability, and improves the sustainability of concrete. The supply of fly ash is decreasing as society becomes less dependent on coal-fired power plants. This has created shortages of fly ash and many people have started to wonder, "Is fly ash going away?"

While the supply of traditional fly ash captured from the flue gas of coal-burning power plants is becoming more limited, there is more than a 170-year supply of usable fly ash that has been buried or is in holding ponds, according to the American Coal Ash Association.[1] This reclaimable fly ash has not previously been used due to low demand or because it is slightly out of specification. Although it may not meet the current ASTM C618 *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*,[2] this material is now being mined, refined, and used in ready-mixed concrete in North Carolina, South Carolina, Texas, and Pennsylvania.

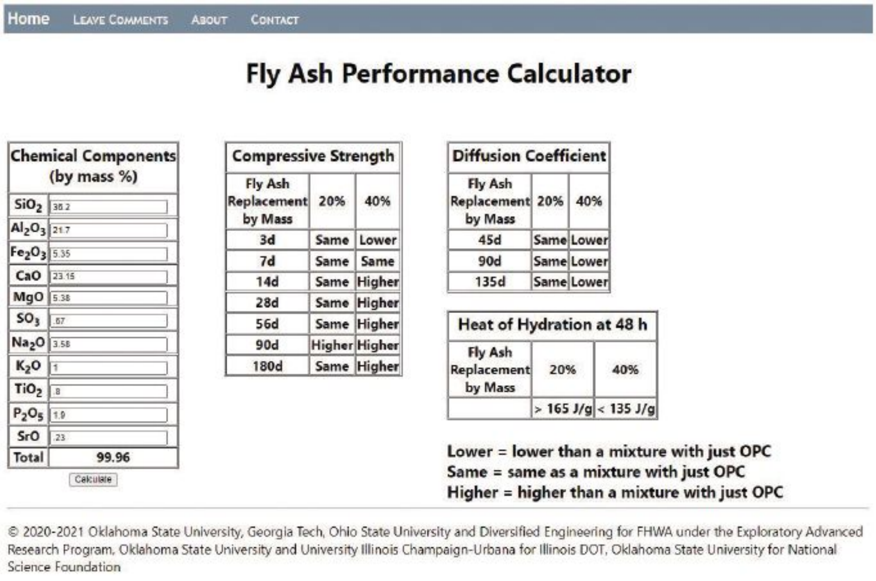
Users are finding that this material has properties that are similar to, and in some cases more consistent than, those of traditional fly ash. Because this material is refined, the producer can control the quality of the fly ash. The companies that sell it use a wide range of proprietary methods to refine the ash. It is not clear whether these refining methods will work on any fly ash source, but satisfactory results are reported for existing sources.

The Federal Highway Administration (FHWA) is sponsoring research project FHWA-PROJ-19-0017, Performance-Based Classification Methods for Reclaimed Fly Ash, to help with the adoption of reclaimed fly ash. Laboratory testing at Oklahoma State University, Georgia Tech, and Ohio State University on 14 different sources of primarily reclaimed Class F fly ash shows that there is little change in the slump or strength gain of concrete with reclaimed fly ash for the first 28 days; however, there is some loss of strength (approximately 10%) at 56 days and 90 days for certain reclaimed fly ash sources. This suggests that, in some cases, concrete with reclaimed fly ash does not achieve the same increase in long-term strength as mixtures with conventional fly ash, but other properties do not seem to be adversely affected. Further work is underway to investigate chloride diffusion and the ability of reclaimed fly ash to suppress the alkali-silica reaction of the concrete, and findings for both seem promising.

One product of the FHWA-sponsored research is a fly ash strength and

Dr. Ley, often with help from his students, has produced many interesting and entertaining YouTube videos on a wide range of topics related to concrete materials and design of concrete structures. In 2019, he posted a YouTube video with the same title as this article (https://www.youtube.com/watch?v=hwtsEUSJ9I0). In the video, he describes fly ash and then discusses fly ash alternatives and the potential for using reclaimed fly ash to continue to improve the durability, constructability, and sustainability of concrete mixtures. For additional information, visit www.tylerley.com/flyashvideos.

Figure 1. A screenshot of the Fly Ash Performance Calculator. When the user inputs the chemical composition of the fly ash, the performance of concrete using the fly ash is predicted relative to a mixture that only contains ordinary portland cement (OPC). Relative performance is indicated for the compressive strength and diffusion coefficient for several ages and two levels of fly ash replacement. An estimate of the heat of hydration is also provided. Figure: Tyler Ley.



permeability calculator, which was developed with machine learning algorithms. This calculator—which is available for free at www.tylerley.com/flyash—uses the oxide content of fly ash from a mill sheet to predict whether a concrete mixture with fly ash will provide performance that is higher than, lower than, or the same as the performance of a concrete mixture that only contains portland cement. This prediction is made for both 20% and 40% fly ash replacement in concrete with ages up to 180 days. **Figure 1** shows a typical data entry screen. The calculator is an outstanding tool that could allow producers or departments of transportation to evaluate a new source of fly ash with a distinctive chemical composition and predict how the concrete will perform. For example, if there were a fly ash shortage on a project, the calculator could be used to help choose a replacement fly ash that maintains the required concrete performance.

This resource also provides much deeper insights than the traditional Class C and F fly ash classifications. The algorithm's accuracy was just over 90% for 35 different fly ashes investigated, and the tool is being extended to use nontraditional fly ash sources.

Several companies are currently investigating the viability of nontraditional fly ash sources. Some of these sources include blended fly ash, ground bottom ash, and natural pozzolans. Blended fly ash combines at least two fly ash sources. Typically, one of the fly ash materials in the blend does not meet the ASTM C618 specification, but the combined material does. Ground bottom ash is a coal-combustion product that is too heavy to be carried up the flue. When this type of ash is ground to a size similar to that of fly ash, the concrete performs well. Natural pozzolans are natural minerals, such as clay and volcanic ash, that are mined, ground, and sometimes heated. These materials have a long history of being used in concrete but have not been used frequently because of cost. All of these materials are being used to make up for the shortfall of fly ash.

With all of these efforts, it is clear that fly ash will not go away, but it will change. New sources of reclaimed or nontraditional fly ash are being brought to the market and will provide new opportunities to improve the durability, sustainability, and cost of concrete.

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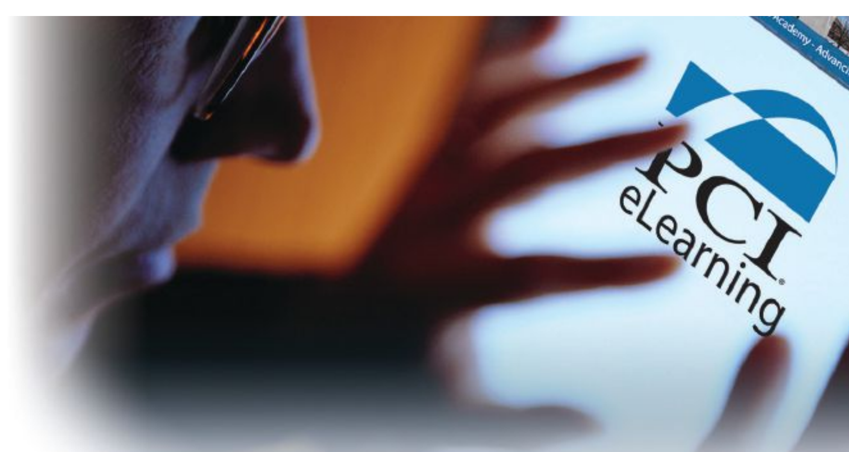

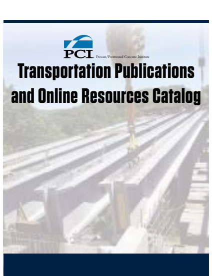

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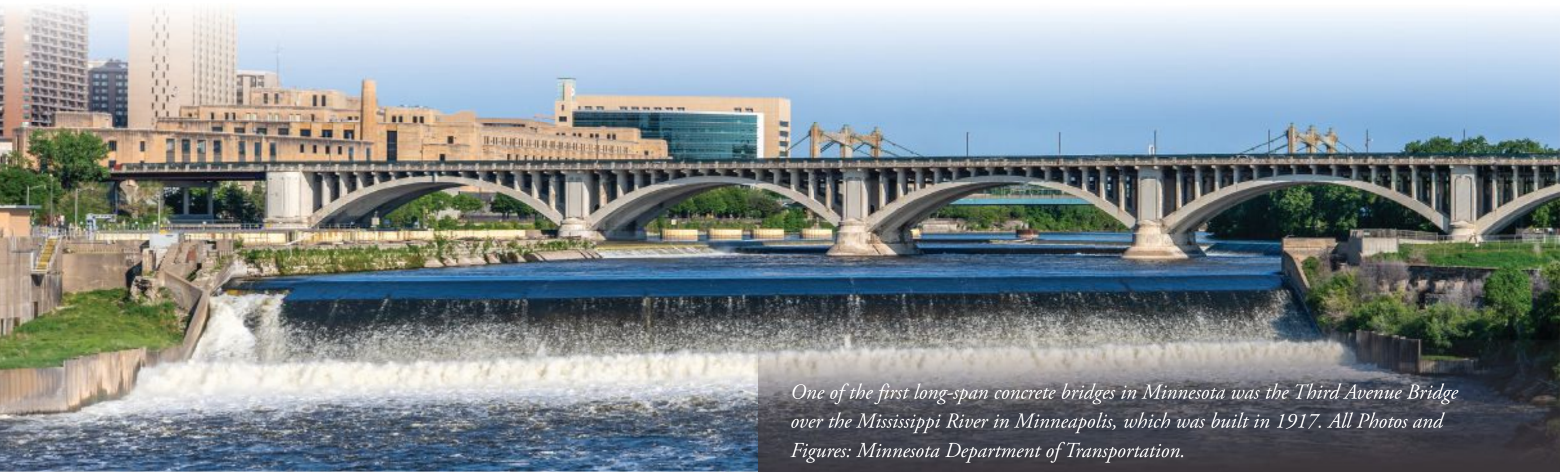
Minnesota

by Kevin Western and Arielle Ehrlich, Minnesota Department of Transportation



One of the first long-span concrete bridges in Minnesota was the Third Avenue Bridge over the Mississippi River in Minneapolis, which was built in 1917. All Photos and Figures: Minnesota Department of Transportation.

Minnesota is the land of 10,000 lakes and more than 10,000 concrete bridges. The Minnesota Department of Transportation (MnDOT) has been constructing and innovating using concrete bridges for more than 100 years. With high-quality aggregates readily available, the use of concrete has long been a logical choice for constructing durable, maintainable structures. The first long-span bridges in Minnesota were concrete arches, including the Third Avenue Bridge carrying Minnesota Trunk Highway (TH) 65 over the Mississippi River in Minneapolis, which was built in 1917.

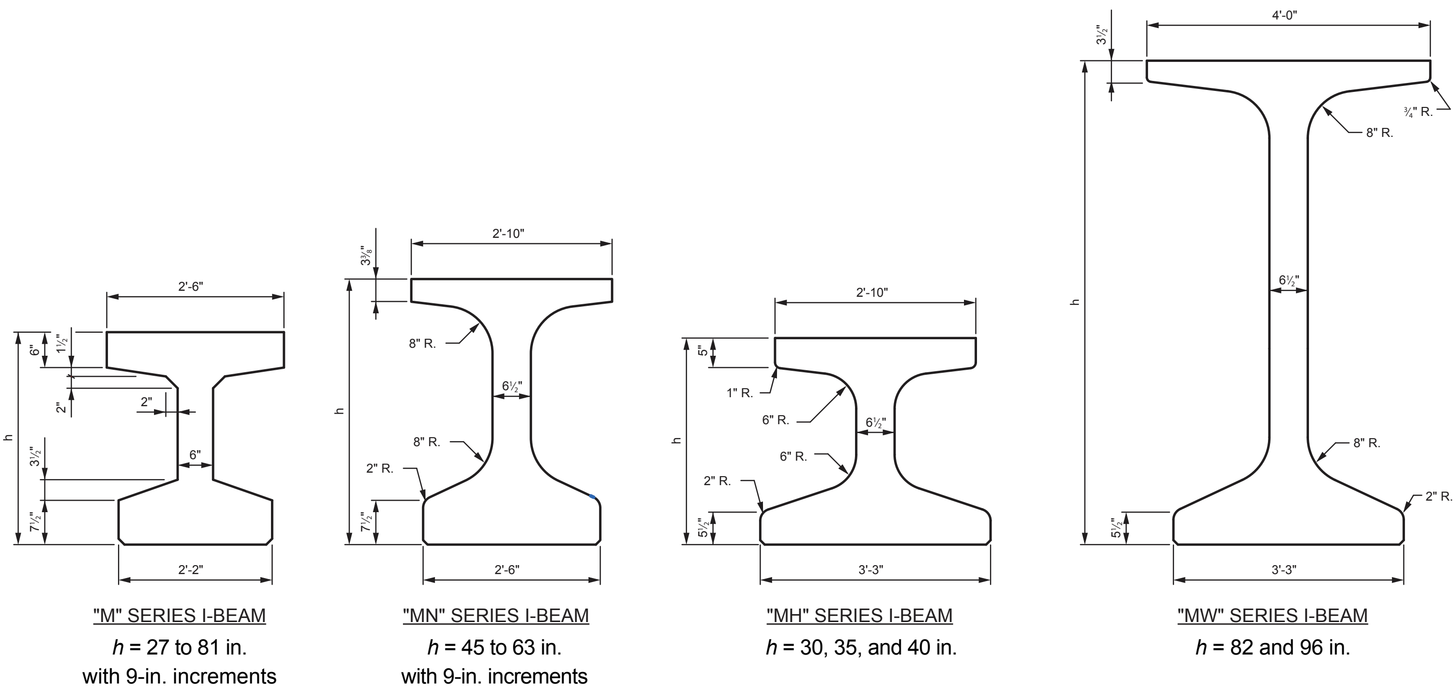
By the 1950s, bridges in Minnesota were typically steel-beam bridges, concrete T-beam bridges, or cast-in-place concrete slab spans. Starting in the late 1950s, MnDOT, along with much of the bridge community, began using precast, prestressed concrete beams. By the 1970s, MnDOT had three regional fabricators, and the prestressed concrete beam became the preferred beam type for the agency because of its maintainability, cost effectiveness, and positive impact on construction schedules.

I-Beam Series

Over the years, MnDOT has constructed bridges with many concrete beam types, including I-beams, quad and double tees, bulb tees, rectangular beams, and, most recently, inverted tees. In addition to changes in geometry, concrete beams have become more efficient through improvements in materials; the maximum allowable concrete design strength has increased incrementally over the years from 5500 to 9500 psi. The I-beam continues to be the beam of choice. MnDOT has developed several series of I-beams over the last 25 years. The first, the M series, was developed in 1995. These had wider flanges than the AASHTO shapes that had been previously used. Over time, additional sizes were added until the depths ranged from 27 to 81 in. with 9-in. increments. Beginning with the first sizes published in 2005, MnDOT issued the MN series. With depths ranging from 45 to 63 in. with 9-in. increments, these beams had wider flanges and radiused, rather than chamfered, corners.[1] They could span farther at a given spacing or be spaced farther apart than the M beams for a given span length.

In the last 10 years, MnDOT has added two more series of prestressed concrete beam shapes. The MW beams have 82- and 96-in. depths for long spans that can exceed 200 ft. Most recently, MnDOT added the new MH series at 30-, 35-, and 40-in. depths. Both the MW and MH series use a 39-in.-wide bottom flange. The MW series uses a 48-in.-wide top flange, and the MH series uses the same 34-in.-wide top flange as the MN series. While the MW series is meant for very long spans, the MH series was developed to fill a gap primarily in the 75- to 105-ft span range. Previously, to meet those span lengths, a steel girder would likely have been necessary to prevent a drastic increase in structure depth. The MH beams, with their shallow depths, can avoid significant grade raises without the need for shoulder piers. (For details of the MH beams and their development, see the Concrete Bridge Technology article in the Summer 2019 issue of *ASPIRE*®.)

The St. Croix Crossing, completed in 2017, was the second extradosed bridge built in the United States. It connects Oak Park, Minn., and St. Joseph, Wisc.



The Minnesota I-beam series provides standard options for a wide range of design challenges.

Segmental Bridges

Although early long-span concrete bridges in Minnesota were arches, more recent long-span structures have been segmental box girders. The earliest uses of this style of bridge in Minnesota were two bridges over the Mississippi River: the Plymouth Avenue Bridge, built in 1980, and the Wabasha Street Bridge, built in 1996.

In 2003, the balanced-cantilever method was used to build the two Wakota Bridges, which carry Interstate 494 over the Mississippi River. Design issues identified during construction required adjustments and modification of details for the second bridge, but despite that, both bridges have been performing well.

Concrete box-girder bridge technology played a crucial role in the emergency rebuilding of the Interstate 35W Bridge over the Mississippi River (for more details, see the Project article in the Fall 2008 issue of *ASPIRE*). The new spans over the river are precast concrete segmental boxes, whereas the spans on the river shore are cast-in-place boxes constructed on falsework. The signature bridge opened to traffic in 2008 just over 13 months after the collapse of the previous steel-truss bridge. The project was completed using a design-build contract. While some of the prospective design-build teams proposed a steel girder bridge, the concrete segmental option was ultimately chosen for construction.

MnDOT has since constructed two more major Mississippi River crossings with segmental concrete bridges: the Dresbach Bridges, which were completed in 2016 and carry Interstate 90, and the Winona Bridge, which was also completed in 2016 and carries TH 43 adjacent to a recently rehabilitated historic truss bridge. (For more information on the Dresbach and Winona bridges, refer to Project articles in the Summer 2016 and Winter 2017 issues of *ASPIRE*, respectively.) Most recently, the St. Croix Crossing, the second extradosed bridge in the United States, opened to traffic in 2017. This bridge, with its graceful, curved piers and scenic St. Croix River setting, has become an attraction in its own right. (For details of the St. Croix Crossing Bridge, see the Project article in the Fall 2018 issue of *ASPIRE*.)

Precast Concrete Culverts

Precast concrete bridge culverts are the original form of accelerated bridge construction in Minnesota. Making up more than 40% of the bridge inventory in Minnesota, precast concrete box culverts are a cost-effective, low-maintenance, and easy-to-install solution for short-span bridges. Standard plans exist for boxes as small as 6 ft wide by 4 ft tall and as large as 16 ft wide by 12 ft tall, and they are used both for stream crossings and pedestrian trails. For areas of the state with little risk of debris accumulation, the boxes are often used in combinations of two or three lines to facilitate bigger crossings and accommodate a larger hydraulic opening. MnDOT is in the process of extending the standard plans to 20-ft spans.

A Bright Future

The future of precast concrete use in Minnesota is bright and exciting. In January 2021, MnDOT published a memo[2] directing designers to use 0.6-in.-diameter, 300-ksi strand tensioned to a maximum of 72% of the specified tensile strength ($0.72f_{pu}$) in all precast, prestressed concrete I-beams. With this change, beams can span farther than with 270-ksi strand. Also, fabricators are able to tension the 300-ksi strands at lower temperatures without needing to preheat the strands in the casting beds; this enables a longer and more cost-effective fabrication season—an important benefit given Minnesota's long winters.

MnDOT is also beginning a switch from harped strands to debonded strands for beams where the ends are encased in concrete diaphragms. MnDOT has historically required the use of fully bonded straight or harped strands only, not allowing debonded strands due to concerns with potential water and chloride intrusion at the beam ends. However, satisfactory in-service performance for beams with debonded strands located in states with similar climates has reduced the agency's concerns about corrosion related to debonded strands. Additionally, straight strands pose less of a safety hazard during fabrication than harped strands, and efficiency is not sacrificed with the use of debonded strands.

An exciting innovation on the near-term horizon for MnDOT and the concrete industry is the use of ultra-high-performance concrete (UHPC) for precast concrete beams. While UHPC can be used to produce extraordinarily long beams, there is tremendous value in using it for shorter-span beams, where bridges can be

The signature bridge that carries Interstate 35W over the Mississippi River is a concrete segmental box-girder bridge completed in 2008. The spans over the river used precast concrete segments, whereas the spans on the river shore were cast in place on falsework.

Kevin Western, the Minnesota Department of Transportation state bridge engineer, stands next to MW series I-beams, which include 96-in. depths for long spans that can exceed 200 ft.

constructed with shallow beams that can span farther than ever without grade raises.

No innovations happen in a vacuum: MnDOT's successful innovations with precast concrete, past and future, are all due to strong partnerships with their fabricators. The fabricators' willingness to consider new possibilities with open minds, make investments where needed, and facilitate change has been crucial.

Minnesota's legacy of innovation in concrete comes from a long line of leaders, including former Minnesota state bridge engineers, who led many of the innovations from the 1980s to today. They helped develop and evolve concrete usage in Minnesota by building a culture of innovation and bravery that is coupled with thoughtful caution and thorough review. This culture, along with the partnerships formed with fabricators, will continue to help Minnesota be a land of many more than 10,000 concrete bridges.

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Kevin Western is the state bridge engineer and Arielle Ehrlich is the state bridge design engineer for the Minnesota Department of Transportation.


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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

https://www.dot.nd.gov/conferences/construction/presentations/2021/CPD-Week-5-March-31/US%2085%20and%20Long%20X%20Bridge%202021%20CPD%20Bridge%20Design.pdf
The Project article on page 26 features the new Long X Bridge on U.S. Highway 85, which crosses the Little Missouri River in North Dakota. A North Dakota Department of Transportation detailed presentation on the project is available at this link.

https://doi.org/10.17226/26172
This is a link to National Cooperative Highway Research Program (NCHRP) Synthesis 562, *Repair and Maintenance of Post-Tensioned Concrete Bridges,* which is the subject of the Concrete Bridge Preservation article on page 38.

http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_562Answers.pdf
The Concrete Bridge Preservation article on page 38 summarizes the results of NCHRP Synthesis 562. As part of the study, state departments of transportation were surveyed about the design, construction, maintenance, and repair of post-tensioned bridge structures. This is a link to the 45 responses to the survey.

https://abc-utc.fiu.edu/wp-content/uploads/sites/52/2017/05/Virginia-Micro-Abutment_05-16-2017.pdf
The "Virginia abutment" is described in the Project article on page 30 featuring the Atkinson Boulevard Bridge over CSX Transportation railroad and Interstate 64 in Newport News, Va. This system allows for contraction and expansion and is self-cleaning. A document about the Virginia abutment can be downloaded via this link.

https://www.iso.org/standard/62085.html
The Perspective article on page 63 describes an engineering firm's approach to improving its quality assurance and quality control processes, which included the decision to pursue ISO 9001 quality management system certification. This is a link to the abstract and description of the ISO 9001 standard.

https://abc-utc.fiu.edu/webinars/research-seminars
In the State article on page 52, the innovative use of ultra-high-performance concrete (UHPC) is mentioned. A recording of the July 30, 2021, webinar "Behavior and Strength of UHPC in Shear," produced by the Accelerated Bridge Construction Center at Florida International University, is available on this webpage.

https://www.asbi-assoc.org/index.cfm/events/MonthlyWebinars
The Concrete Bridge Technology article on page 42 discusses standardizing details for segmental concrete box-girder bridges. This link provides access to American Segmental Bridge Institute webinars such as "Detailing Segmental Concrete Box Girders for Constructability" and "Load Resistance Factor Rating of Concrete Segmental Bridges."

https://www.fhwa.dot.gov/environment/sustainability/resilience/publications/gbp_june_2017/index.cfm
This is a link to the report "Transportation Infrastructure Resiliency: A Review of Practices in Denmark, the Netherlands, and Norway" (FHWA-HEP-17-077), which is the basis of the FHWA article on page 58.

https://www.10thavebridge.com/construction-updates
This is a link to a Construction Updates webpage for the Tenth Avenue Bridge rehabilitation project in Minneapolis, Minn., which is the subject of the Creative Concrete Construction article on page 46. Project update presentations and videos are available in which the suspended platforms described in the article are visible.

http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07(307)_AppendixA-GUIDE.pdf
The Perspective article on page 20 presents Washington State Department of Transportation's policies and criteria for repairing or replacing prestressed concrete girders damaged while in service. Other resources for the evaluation and repair of damaged girders include "Guide to Recommended Practice for the Repair of Impact-Damaged Prestressed Concrete Bridge Girders," published as part of NCHRP Project 20-07. The guide is available for downloading via this link.

http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-07(307)_FR.pdf
This is the link to the final report for NCHRP Project 20-07, "Updated Research for Collision Damage and Repair of Prestressed Concrete Beams," which is relevant to the topics discussed in the Perspective article on page 20.

OTHER INFORMATION

http://onlinepubs.trb.org/Onlinepubs/nchrp/docs/SCAN19-01rev3.pdf
NCHRP Project 20-68D, the U.S. Domestic Scan program, is intended to facilitate innovation among transportation agencies by face-to-face interaction. Domestic Scan 19-01 brought together representatives from 12 state agencies to share lessons learned in bridge design, construction, and maintenance. This link accesses the Scan 19-01 report, "Leading Practices for Detailing Bridge Ends and Approach Pavements to Limit Distress and Deterioration."

EDITOR'S NOTE

A slight correction to the article about the John F. Kennedy Memorial Causeway Bridge in the Summer 2021 issue of* ASPIRE® *(page 20) is in order. The bridge was the third precast concrete segmental bridge built in the United States. In addition to the scale model constructed and tested at the University of Texas at Austin, it was preceded by construction of a one-tenth-scale model of the proposed "Three Sisters Bridge" across the Potomac River between Washington, D.C., and Virginia, which was built in the Portland Cement Association's Structural Laboratory in 1970 and 1971. Details of that project are described in a* PCI Journal *article available at https://doi.org/10.15554/pcij.11011971.70.84.

Transportation Infrastructure Resiliency: A Review of Practices in Denmark, the Netherlands, and Norway

by Robert Kafalenos, Federal Highway Administration

To promote system resiliency and prevent road destruction, a new culvert in Norway was designed using design flows that reflect engineering judgment, lessons learned from past flooding, and anticipated future precipitation increases. All Photos: Federal Highway Administration.

Extreme weather events and changes in climate pose significant challenges to the highway transportation community in the United States. From heat waves and droughts to storm surges, these events can not only damage roads and bridges but also result in large repair costs and disrupted travel. State and local transportation agencies across the country have begun to assess the vulnerabilities that their roadway systems and operations face from these climate risks. While there are some notable examples of cities and states using climate science and technology to implement responses, many agencies are early in the process of understanding climate vulnerabilities and implications and developing adaptation and resilience strategies.

Learning from Abroad

Transportation agencies in other countries face similar and sometimes more urgent climate challenges to their transportation infrastructures. Some of these countries have made significant progress in developing strategies for reducing climate risks at the national level and have begun integrating climate projections into design criteria and specifications for transportation infrastructure projects. Some have also employed systematic methods to address some of the inherent uncertainties in predicting climate changes and to manage the associated risks.

To help inform and advance similar efforts in the United States, the Federal Highway Administration (FHWA) undertook a Global Benchmarking Program (GBP) study in 2015 to learn how transportation agencies in other countries are adapting their roadway infrastructures to severe weather events and changes in climate, and to identify innovative and best practices to help advance the development and implementation of resilience strategies in the United States.[1] This article, which is based on the GBP study, summarizes key policies and practices identified through the study and how FHWA is putting this knowledge to use for domestic benefit. Note that some practices may have been updated since the study's publication.

As part of the study, FHWA conducted technical field visits and discussions with officials from transportation agencies in Denmark, the Netherlands, and Norway. These countries were selected based on information gathered from a "virtual review," which used webinars to gather information from a broad range of countries and to identify where climate adaptation and resilience activities have been implemented and have yielded demonstrable results.

Policies

The GBP study observed two policies across all three countries that catalyzed progress in developing and implementing resilience strategies:

- **Clear national government support for infrastructure resilience:** Climate change is a primary motivator, with little resistance or controversy, for project-level decisions. Strong national government support for infrastructure resilience facilitates action by the transportation agencies. In addition, each of the three countries has climate resilience strategy documents that provide direction to government agencies.

- **Close collaboration between science and transportation agencies:** Climate scientists and transportation engineers and planners work jointly to develop, interpret, and apply climate projections to transportation design processes. In addition, meteorological and science agencies have mandates, resources, and funding to provide climate projections and interpretation to support transportation agencies and others.

Practices

In Denmark, the Netherlands, and Norway, practices for integrating climate projections into highway planning and design procedures include the following:

- **Incorporating future projections:** In Denmark, roads are often designed to accommodate a 25-year rainfall event. However, as a warmer atmosphere holds more water, heavy rainfall events are projected to become even heavier. The Danish Road Directorate uses climate model projections to update future storm depths. The current 25-year storm in Denmark drops 58 mm (2.3 in.) of rain, but by 2050, the 25-year storm is projected to dump 65 mm (2.6 in.) of rain. When building a road with a design life extending to 2050 or beyond, Denmark now considers the depth of the future 25-year storm, not just current conditions.
- **Using information on the direction of change:** There is generally much greater certainty regarding the direction of change than the exact magnitude and timing of change. Knowledge of the expected direction of change (for example, increasing or decreasing precipitation) is sufficient for some decisions. For instance, based on knowledge that debris and water flows are expected to increase as the climate changes, Norway has installed debris deflectors or screens on newer projects to keep debris out of drainage systems, and energy dissipaters in channels and culverts to reduce increased velocities.
- **Applying climate factors:** Norway has multiple alternative climate factors that are used by its climate science agencies (the Norwegian Water Resources and Energy Directorate [NVE] and the Norwegian Meteorological Institute [MET]) and the Norway Public Roads Agency (NPRA). In Norway, the expression "climate factor" conveys the relationship between the value of a parameter (for example, runoff or precipitation) today to the value of that parameter in the future under the influence of climate change. The NVE applies climate factors to watershed flows, and the MET applies them to precipitation. The NPRA recognizes these factors but does not necessarily use them in design. Currently, the NPRA applies a climate factor of 1.0 to 1.5 to its design flows to reflect engineering judgment, past flooding, and anticipated future precipitation increases. However, the factors may be revised as NPRA's highway design manual is updated. For now, the climate factor for installations that have a life expectancy of 100 years is 1.3 for a 10-year return period of precipitation, 1.4 for 100 years, and 1.5 for 200 years. The NPRA advises its regional offices on the best data to use, and recommends making calculations based on several combinations of input parameters, performing a rough estimate of costs, and choosing the most cost-effective solutions.
- **Updating technical guidance:** The NPRA added consideration of climate change to its manuals on project planning, design, operations, maintenance, and network management. For instance, the maintenance manual recommends implementing climate adaptation measures as part of scheduled maintenance. Norway also developed new guidelines for hazards exacerbated by climate change: rockslides, debris flows, slush avalanches, and snow avalanches. Finally, Norway is creating a drainage textbook incorporating new requirements on climate adaptation, erosion, pollution control, and traffic safety.
- **Adjusting rainfall depth-duration-frequency curves:** Rather than using climate factors, the Netherlands' transportation agency increases rainfall depth-duration-frequency curves by 30%. This percentage is based on the Royal Netherlands Meteorological Institute's analysis of precipitation projections for 2050 using a warmer climate scenario.

Managing Uncertainty

Denmark, the Netherlands, and Norway are moving forward with risk reduction by managing uncertainties rather than allowing uncertainties to stymie action. Although there is scientific consensus that the climate is changing, there is uncertainty regarding the exact magnitude and timing of changes. Areas of uncertainty include the level of greenhouse gas emissions humans will produce in the future, natural climate variability, and the computer models scientists use to model Earth's many complex physical processes. Uncertainty is managed in the following ways:

- **Scenario analysis:** The Royal Netherlands Meteorological Institute developed four climate change scenarios for use in the Netherlands. This allows agencies to account for uncertainty by considering the performance of agency policies under a broad range of plausible scenarios. Two scenarios reflect a future with moderate warming, whereas the other two scenarios reflect a future with higher levels of warming. Temperature and precipitation projections for each scenario are expressed not as single values, but as ranges reflecting natural variability and model variability.
- **Flexible adaptation pathways (or adaptive management):** Researchers in the Netherlands advocated choosing flexible strategies with time frames that allow for course

Because debris and water flows are expected to increase as the climate changes, Norway has installed debris deflectors or screens on newer projects (top) to keep debris out of drainage systems, and energy dissipaters in channels and culverts (bottom) to reduce velocities.

changes as new information emerges. The decision tree or pathway is mapped out over a timeline. Transfers from one adaptation strategy to another can be made at various points in time. As the climate changes, some adaptation strategies have a limited window of effectiveness, at which time they run into terminals or tipping points and new pathways must be followed. Each of the pathways can be rated qualitatively for cost effectiveness and possible unwanted side effects.

- **Conservative assumptions:** As a precautionary approach, the three countries use the high end of the range of national climate projections.

Study Benefits

FHWA has used knowledge gained through the GBP study in the following ways to address infrastructure resilience challenges in the United States:

- FHWA applied findings from the study to the update of its "Vulnerability Assessment and Adaptation Framework,"[2] which guides transportation agencies in assessing the vulnerability of transportation assets and implementing strategies to reduce risks. The framework update also incorporated all three countries' insights and experiences from using ROADAPT (roads for today, adapted for tomorrow) guidelines,[3] the European equivalent of FHWA's framework.
- Danish, Dutch, and Norwegian approaches to choosing the more extreme greenhouse gas emissions scenarios associated with future precipitation projections have influenced the FHWA narrative on scenario selection associated with more critical assets in a major update of its technical guidance document, Hydraulic Engineering Circular 17, "Highways in the River Environment."[4]
- Observing the close collaboration between science and transportation agencies has encouraged FHWA to increase its cooperation with federal agencies such as the U.S. Geological Survey, the National Weather Service, and the U.S. Army Corps of Engineers.
- Study findings guided FHWA's work to develop procedures for addressing climate change in project-level scoping studies.
- The study was an important step in gathering needed technical information for implementing FHWA Order 5520,[5] which establishes policies related to preparedness and resilience to extreme events associated with changes in climate.

Conclusion

FHWA's responsibilities include developing, prioritizing, implementing, and evaluating risk-based and cost-effective strategies to minimize risks and protect critical infrastructure using the best available science, technology, and information. The GBP study was an important step in gathering needed technical information for implementing this requirement.

For additional related information, see also FHWA's TechBrief on climate change adaptation for pavements[6] and its Transportation Engineering Approaches to Climate Resiliency (TEACR) Study.[7]

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Approved Changes to the Ninth Edition AASHTO LRFD Bridge Design Specifications

by Dr. Oguzhan Bayrak, University of Texas at Austin

The 2021 virtual meeting of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Bridges and Structures (COBS) took place July 12–16. This meeting saw the approval of 11 working agenda items (WAIs) prepared by AASHTO Technical Committee for Concrete Design (T-10) that had been developed within the past two years. This article covers those WAIs, which correspond to upcoming changes to the provisions for concrete bridge design in the *AASHTO LRFD Bridge Design Specifications*[1] that will appear in the 10th edition when it is published in a few years. Because the development period was longer than usual, the number of approved WAIs is much larger than what has been typical for Committee T-10. Therefore, this article only summarizes the 11 approved WAIs; detailed discussions of the items will be provided in LRFD articles in upcoming issues of *ASPIRE*®.

1. **WAI 133: Deflection and Camber Calculations**
   The calculation procedure provided in Article 5.6.3.5.2 of the current AASHTO LRFD specifications underestimates instantaneous deflections of reinforced concrete members with low flexural reinforcement ratios. In addition, the current AASHTO procedure does not reflect the reduction of stiffness caused by cracking that is the result of restraints imposed by the structure and loading of early-age concrete during construction. The proposed revisions are intended to improve the estimation of instantaneous deflections under these conditions, while not significantly affecting the predictions at higher reinforcement ratios.

   The design provisions for estimating time-dependent deflections have been modified to reflect what has been specified in the American Concrete Institute's *Building Code Requirements for Structural Concrete* (ACI 318)[2] for many years. Applying a multiplier of 4.0 to the instantaneous deflection to obtain time-dependent deflection, which currently appears in Article 5.6.3.5.2 of the AASHTO LRFD specifications, has been shown to be inaccurate and does not adequately address all concrete strengths, member sizes, and exposure conditions. The implementation of new design provisions improves the accuracy of calculations, including the use of creep and shrinkage coefficients, and results in a better prediction of time-dependent deflections.

2. **WAI 200: Tensile and Compressive Stress Limits and Reinforcement Design for Allowing Higher Tensile Stresses**
   There are three issues addressed in this WAI: inconsistency in tensile stress limits, inconsistency in determining whether bonded reinforcement is sufficient to allow the use of increased tensile stress limits, and providing relief from high concrete strength requirements stemming from calculated compressive stresses at the extremities of the cross section when lateral bending is present and explicitly considered. Implementation of the changes covered by this WAI will establish consistency in tensile stress limits and associated crack-control reinforcement. Furthermore, a slightly increased compressive stress limit will provide relief when checking temporary stresses at the corners of prestressed concrete member cross sections during handling, transportation, and erection.

3. **WAI 202: Seismic Design Rule Clarifications**
   The progression of seismic design provisions over the years inadvertently created language in various articles of Section 5 of the current AASHTO LRFD specifications that can potentially be misinterpreted. More specifically, some design criteria and seismic detailing options do not provide clear direction for best practices and preferred details. Furthermore, minimum or maximum limits of applicability of some details are not explicitly articulated. Within this context, WAI 202 clarifies language in a number of articles in the AASHTO LRFD specifications to improve the seismic design provisions of Section 5.

4. **WAI 203: Confinement Reinforcement: Spirals, Hoops, and Ties**
   Confinement reinforcement can be provided in various forms. Spirals, hoops, ties, and cross ties are used in various applications, as dictated by governing loading conditions and/or geometric design limitations. This WAI provides a clear definition of each type of transverse reinforcement in compression members. Furthermore, it addresses some organizational issues within Section 5.

5. **WAI 204: Regions Where Minimum Transverse Reinforcement Is Required**
   Except for slabs, footings, and culverts, Article 5.7.2.3 of the current AASHTO LRFD specifications requires that a minimum amount of transverse reinforcement be provided when the factored shear exceeds the limit expressed in Eq. (5.7.2.3-1). It is not clear whether this requirement applies to conventional retaining walls. Because Article 5.2 defines a slab as a component having a width that is at least four times its effective depth, retaining walls typically meet the definition for a slab. As a result, they are exempt from the minimum transverse reinforcement requirements of Article 5.7.2.3. WAI 204 clarifies minimum transverse reinforcement requirements for walls.

6. **WAI 206: Strut-and-Tie Modeling (STM) vs. Sectional Design of Sections Near Supports**
   Load transfer near structural supports is a function of the loading type (concentrated or distributed loads) and structural geometry. This WAI provides clarification on what types of loads impose additional demands on stirrups near the supports and what types of loads directly flow into the supports via the formation of direct struts. Through the clarifications provided by WAI 206, the confusion between use of sectional design methods and STM should be reduced or eliminated.

7. **WAI 209: Continuity Design of Prestressed Concrete Beams**
   Creating continuity over the piers for precast, prestressed concrete girder bridges is preferred by some owners because this detail minimizes moisture penetration through the deck onto the ends of the beams and reduces maximum positive moment in the girder. The continuity detail where some of the girder bottom strands are extended into cast-in-place concrete diaphragms at the piers is preferred by some owners and used routinely in bridge construction. Proper structural details have been shown to be effective in controlling bottom fiber cracking caused by restraint moments due to volume changes such as creep, shrinkage, and temperature gradient. That being said, analysis for these effects can be complex. The purposes of this WAI are to provide simplified equations for the value of the restraint moment at the diaphragms and the required reinforcement to control cracking, and to remove the requirement that the age of the girder at continuity be at least 90 days.

8. **WAI 210: Post-Installed Anchors**
   ACI 318-19[2] includes changes to the anchor design section. ACI 318-19 provisions now include design provisions for shear lugs comprising a steel element welded to a base plate and for post-installed concrete screw anchors, as well as qualification testing for anchors. In a reorganization of ACI 318-19 anchor design, Chapter 17 specifies all design, material, testing, anchor, anchor spacing, edge distances, and acceptance requirements, as well as geometry and depth limitations. Information concerning specification and inspection has been moved to the appropriate sections of Chapter 26 in ACI 318-19. WAI 210 establishes consistency between the AASHTO LRFD specifications and ACI 318-19 provisions.

9. **WAI 212: Mechanical Coupler Use for A1035 Material**
   Reinforcement and mechanical connections using ASTM A1035/A1035M[3] material have been successfully tested by the Concrete Reinforcing Steel Institute and have been used by owners. The test results show that the material meets the criteria set in National Cooperative Highway Research Program Project 10-35.[4] This WAI revises the AASHTO LRFD specifications to allow the use of mechanical couplers for ASTM A1035/A1035M reinforcement.

10. **WAI 215: Struts Crossing Cold Joints**
    Recent events have highlighted the importance of properly evaluating and detailing cold joints;[5] however, Article 5.8 of the current AASHTO LRFD specifications, Design of D-Regions, does not explicitly require that struts crossing cold joints be checked for shear friction at that interface. This modification will require that such cases are checked in design and/or assessment, and will help prevent unconservative capacity predictions from being made where struts cross cold joints. In this way, WAI 215 brings the AASHTO LRFD specifications into better alignment with international design guidance.[6]

11. **WAI 216A: Concrete Creep and Shrinkage**
    This WAI provides clarification on creep and shrinkage estimations. While different creep and shrinkage estimation techniques may be appropriate for different bridge types, this WAI makes it clear that for segmentally constructed bridges, estimates of shrinkage and creep may be made using the provisions of the *fib Model Code for Concrete Structures 2010*[7] or the *CEB-FIP Model Code 1990*.[8]

These 11 working agenda items are intended to improve structural design of concrete bridges by simplifying the design process, reducing ambiguity in design provisions, and establishing consistency. Upcoming articles will cover these items in greater detail to provide the background and context for these changes. Until then, stay in good health during these challenging times!

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3. ASTM Subcommittee A01.05. 2020. *Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement.* ASTM A1035/A1035M. West Conshohocken, PA: ASTM International.

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Does Your QA/QC Process Need a Fresh Look? Ours Did!

by Craig Finley, FINLEY Engineering Group

It has become a seemingly weekly occurrence that somewhere in the world, an engineering failure has taken one or more lives and led to public distrust of engineered construction. As an industry and as professional engineers, the quality of our engineering work must be done to the best of our ability, and too often this has not been the case. I believe every professional engineer and engineering organization should ask themselves, "Does our quality assurance/quality control (QA/QC) process ensure mistakes are caught before an accident occurs?"

The Florida International University (FIU) pedestrian bridge collapse hit home with us. Although we were not involved in the project, we knew it was time to seriously review our quality control process. We did not want the "next time" to be us or a FINLEY project.

We thought we had a good QA/QC process, but we also knew that our "good" may not be good enough, and so we started a top-down/bottom-up review. This included:

- reviewing our QA/QC manual and documentation,
- reviewing how mistakes are found and the process of correcting them,
- comparing design team reviews with external reviews,
- reviewing staff training and QA/QC performance,
- reviewing training and expectations for quality and checking standards,
- assessing management and staff commitments to a FINLEY quality culture, and
- asking select clients to fill out a QC/QA survey to learn, "What are our clients' impressions of FINLEY's work product?"

From this self-investigation and internal process review, we found that, while we were successful with our QA/QC approach, we could do better. We wanted to have a culture that demands quality across the board—on all of our processes and within the whole organization.

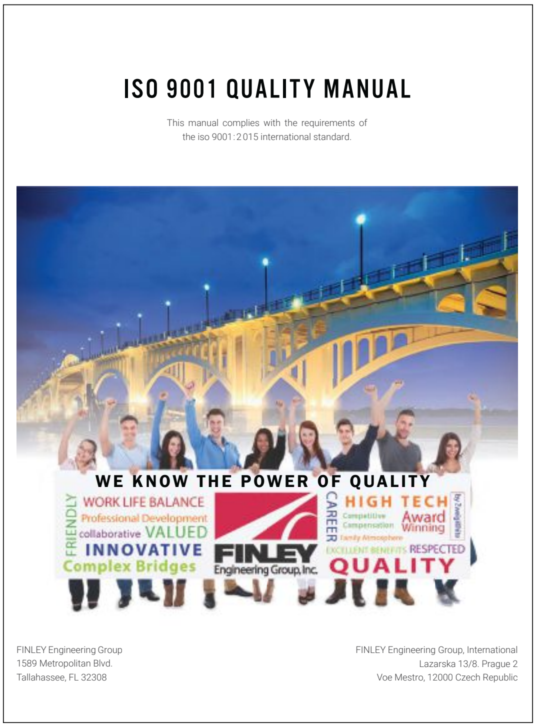
We had been using the tried-and-true industry-standard quality philosophy based on the "check print—red, green, yellow" approach; however, this relies on paper copies and colored markers. We have now moved past a typical computer-aided design and drafting technician/production workflow; our engineers produce everything in three dimensions within a bridge information modeling (BrIM) workflow. While the newer workflow increased quality by eliminating frivolous and repetitive drafting mistakes, the QA/QC process was taking an increasingly larger percentage of production time. The challenge was, how do you verify a BrIM model and ensure the programing is correct?

The foundation of our QA/QC process was outdated, and our workflow had advanced into a BrIM environment. We needed a major update to our QA/QC manual and procedures to match our digital workflow. This also led to improved training for and management of these new processes. If you are considering moving to a BrIM workflow or using automated drafting, we suggest that you put revising QA/QC processes near the top of your implementation plan. There will be more changes than you initially expect, but the improvement in efficiency and quality is huge.

The FIU bridge collapse also informed us how the world has changed and how engineering could be front-page news. Ten minutes after the collapse, we knew about it. Even though we were not involved, the media were calling our office looking for information. Then we received additional calls from others in the industry asking for our opinion and thoughts on the collapse. These inquiries came into several levels of our organization and reinforced to us that perception is reality to our clients. We felt unprepared for this new climate and needed to make some improvements.

We have had a good and effective disaster plan for such things as hurricanes, ransomware/server attacks, violence in the workplace, fire, and COVID-19, but we did not have anything planned should there be an accident on a project we were involved with. We saw this as a QA/QC risk, so we brought in a public relations expert to help us develop a plan and train our staff on how to respond to the media.

We decided to monetarily incentivize our QA/QC process, which quickly got everyone's attention and demonstrated why great quality makes for good business. We use a project incentive program, with project bonuses up to 10% of salary, on all projects with a fee over $100,000. We set metrics for quality, such as delivering an error-free design or a design requiring one revision or rework, and we require a



Cover of the FINLEY Quality Manual that was developed as part of the ISO 9001 certification process. Figure: FINLEY Engineering Group.

reference or recommendation from the client's project manager to confirm achievement of the metrics. A mistake that makes it to construction will cancel the whole project incentive for the whole team, regardless of the source of the mistake. Client feedback is a crucial part of the project incentives because what our clients have to say is very important to us. We have received some good feedback to improve our process and benchmark our performance.

We also decided that certifying to the ISO 9001[1]—the international standard that specifies requirements for a quality management system—would be another step in the right direction. We elected to pursue ISO 9001 certification because it provides a process that generates a 360-degree view of our quality program as a whole. We also needed to add client input into our program. We had already established a solid QA/QC policy and our work products are of the highest caliber, but we needed a better way to communicate that quality to our clients. More importantly, we needed a way for our clients to provide formal feedback so that we can continually improve our products and overall quality.

We worked with a third-party consultant, who provided some advice and helped fine-tune the documentation required for ISO 9001 certification. They guided us through the certification process to help ensure that our end processes are easily managed and maintained, giving us the opportunity to continually improve our internal processes and quality for our clients.

In summary, I think taking a fresh look at our QA/QC process has been very beneficial and has made our firm better. The multifaceted approach worked very well, and before the end of the first year of implementation, we had developed a quality culture that was understood and accepted by everyone on the team.

If you are considering this worthwhile endeavor, we suggest you consider these key points:

- It took several months to put everything in place, and we required the help of outside consultants.
- A "not me/not us/not now" attitude will not lead to a better product.
- We must have a strong sense of professionalism, demand a company quality culture, and realize that quality is good for business.
- The ISO 9001 program is excellent and designed for any organization in any business to achieve the highest level of a quality management system. It definitely has a place in U.S. companies and is recognized internationally as the "gold standard" of quality system certification.

Reference

1. International Organization for Standardization (ISO). 2015. *Quality Management Systems—Requirements*. ISO 9001:2015. Geneva, Switzerland: ISO. https://www.iso.org/standard/62085.html.