ASPIRE®

THE CONCRETE BRIDGE MAGAZINE

SUMMER 2021

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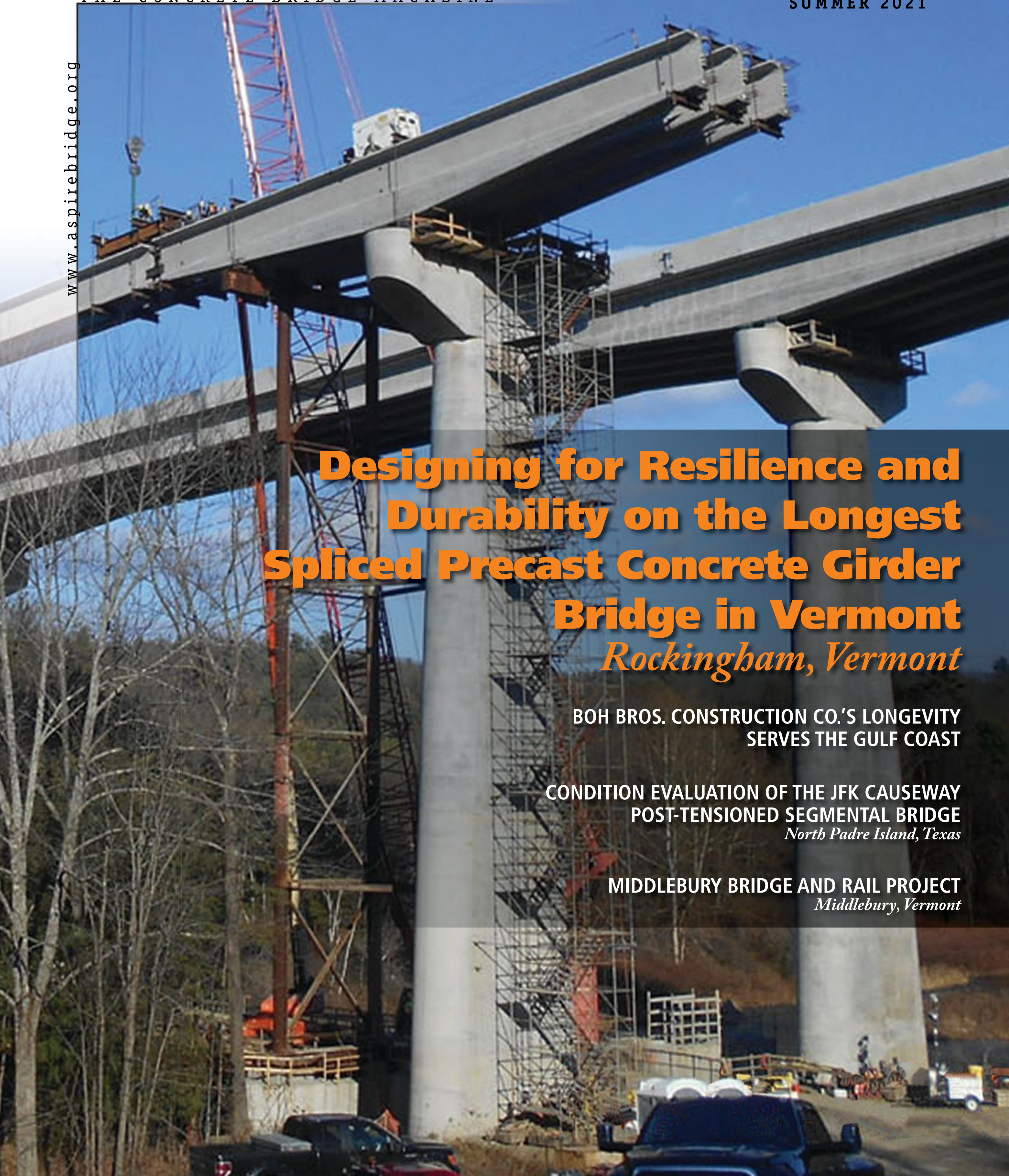

Designing for Resilience and Durability on the Longest Spliced Precast Concrete Girder Bridge in Vermont

Rockingham, Vermont

BOH BROS. CONSTRUCTION CO.'S LONGEVITY SERVES THE GULF COAST

CONDITION EVALUATION OF THE JFK CAUSEWAY POST-TENSIONED SEGMENTAL BRIDGE
North Padre Island, Texas

MIDDLEBURY BRIDGE AND RAIL PROJECT
Middlebury, Vermont

Photo: Texas Department of Transportation.

Photo: VHB.

Photo: HDR.

Features

Departments

Photo: Flatiron Construction Co.

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EDITORIAL

Photo: PCI.

Our Fundamental Principles: Ethics and Quality

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

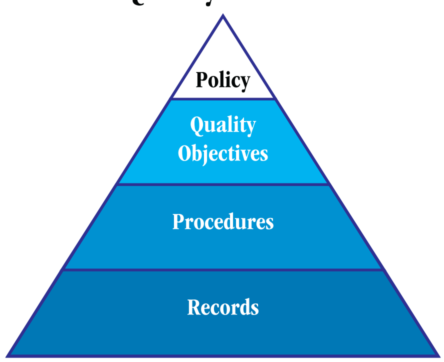
The American Association of State Highway and Transportation Officials (AASHTO) has released a video profile of Victoria Sheehan, the 2020–2021 AASHTO president.[1] She has been commissioner of the New Hampshire Department of Transportation (DOT) since 2015. Sheehan has a master's degree in structural engineering and architecture, and started her career in the accelerated bridge construction program at the Massachusetts DOT. It's pretty neat to see a structures professional in the top agency leadership role. Please take a moment to watch the video and listen to Sheehan's thoughts on diversity, technology, and other changes that will impact core functions of the transportation industry. She emphasizes the need to expand the skill sets of our workforce and to fund a stable program with a long-term horizon, showing leadership the benefits of "predictability for longer-term planning."

Watching the AASHTO video got me to thinking again about the fundamental principles of delivering well-designed, high-quality products and assets to our customers/owners. In the Spring 2021 issue of *ASPIRE*®, Dr. Richard Miller authored a Professor's Perspective on ethics and judgment and how, as a university professor, he approaches the topic with his engineering students.[2] In this issue on page 51, Dr. Anna Pridmore continues the discussion with a Perspective on the new American Society of Civil Engineers (ASCE) Code of Ethics[3] and what it takes to foster an ethical culture and impact behavior. She reminds us of the importance of fostering a culture of empowerment and communication that will impact behavior within companies and organizations. In her words, "Engineers can drive culture shifts that empower us and others to talk about potential and ongoing problems."

Organizations can strengthen and support our individual professional ethics by sustaining a culture of quality. A quality company culture starts with leadership that sets and upholds solid policies, with clearly stated quality objectives and standard operating practices. A fundamental tenet is that all quality systems begin and end with complete and comprehensive records. Over the years, I've worked with colleagues who work to maintain transparency in every aspect of our projects, starting with our plans and records. Preserving these critical documents for years after projects are delivered is key. Without good record-keeping, we cannot trace the designs and calculations used in projects or understand how past decisions affect the future of our transportation infrastructure.

How do we ensure that the programs we have in place live up to the demands of our profession? I suggest that we start with the "AISC/PCI White Paper on Quality Systems in the Construction Industry"[4] as a primer. This collaborative report is an easy read, provides a bit of background on the roles of technical institutes and certification programs, and outlines the 12 elements of comprehensive quality systems for a technical institute's plant certification program.

Quality Culture



A variety of models are available to help us establish quality programs and systems in our organizations. At their core, quality programs demand attention to detail, standardized procedures/work instructions, and an assurance that provided guidance is followed. This outlined approach provides the guidance for establishing the organizational stewardship (body of knowledge) to enhance established quality programs or aid in building a new program starting from ground zero.

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The design-build team evaluated several alternative structure types for the new twin bridges on Interstate 91 near Rockingham, Vt., ultimately selecting precast concrete spliced-girder bridges that will exceed the 100-year service life requirement. Photo: HDR.

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In Dr. Miller's article on teaching ethics, he explains how he uses the example of an expressway dividing a neighborhood to frame the discussion with his students of the societal, environmental, and economic ramifications of their work (both locally and globally). His students must navigate this engineering dilemma and consider the effects and influence this solution could have on adjacent established communities. They must take into account the human aspects of their designs. This example led me to wonder: Is it at this juncture where engineering decisions shift from science to art?

Now let's talk through indirect impacts: what happens when a seemingly minor misstep becomes a global issue? On March 23, 2021, the *Ever Given*, one of the largest cargo ships in the world, ran aground, essentially shutting down global shipping through the Suez Canal until the ship was freed on March 29. The inability to move cargo through the canal had the potential to cause significant and costly delays for construction industry-based projects globally. Perhaps it delayed the delivery of construction material and heavy equipment to your projects.

If your project is affected, will that cause an out-of-sequence issue? Are you and your team prepared to adjust? During times of uncertainty, our ethics may be tested, and our reliance on quality procedures, programs, and systems can save the day. Organizations and companies must cultivate a dual mindset of both rigorous adherence to standards and quality control/assurance procedures as well as being open to the spontaneous communication of ideas and concerns. If your organization is contemplating joining forces with an entity that doesn't take open communication, ethics, quality management, quality assurance, and quality control seriously, consider another collaborator.

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PCI Ultra-High-Performance Concrete Workshop set for September

PCI is hosting an Ultra-High-Performance Concrete Workshop Tuesday, September 21, 2021. This one-day workshop will gather experts from across the precast concrete industry to discuss various research and development initiatives for the implementation of ultra-high-performance concrete (UHPC) in precast concrete components.

The workshop will cover design considerations for architectural and structural precast UHPC components, such as UHPC material selection for nonproprietary mixture designs, characterization and quality control testing of UHPC, and production and fabrication of precast UHPC components.

The workshop will be at Loews O'Hare in Rosemont, Ill. For more information, go to https://www.pci.org/events

CONTRIBUTING AUTHORS

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CONCRETE CALENDAR FOR SUMMER 2021

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.

July 11–15, 2021
AASHTO Committee on Bridges and Structures Annual Meeting
Online

July 26–August 4, 2021
AASHTO Committee on Materials and Pavements Annual Meeting
Online

August 10, 2021
2022 PCI Design Awards
Submission deadline

September 13–16, 2021
2021 Western Bridge Engineers Seminar
Online

September 13–18, 2021
PTI Certification Training: All Levels
Phoenix, Ariz.

September 20, 2021
ASBI Grouting Certification Training
Online

September 22–25, 2021
PCI Committee Days and Technical Conference
Loews Chicago O'Hare Hotel
Rosemont, Ill.

September 26–30, 2021
AREMA 2021 Annual Conference with Railway Interchange
Online

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

October 17–29, 2021
ACI Fall 2021 Convention
Hilton Atlanta Downtown
Atlanta, Ga.

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

November 15–20, 2021
PTI Certification Training: All Levels
Austin, Tex.

December 8–10, 2021
Accelerated Bridge Construction Conference
Online

January 9–13, 2022
Transportation Research Board 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
Kansas City Convention Center
Kansas City, Mo.

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

A HELPFUL HINT

For a complete list of search results in the online version of *ASPIRE*® users must search from within an issue.

Once an issue is open, click the search button and type the search term. Then click the folder button to search all archived issues.

This will return all results of the search from all past issues of *ASPIRE*.

Contractor's Longevity Serves the Gulf Coast

For more than 100 years, family-owned Boh Bros. Construction Co. has shaped the region surrounding its New Orleans home base through heavy civil and concrete bridge work that connects the region

by Monica Schultes

Boh Bros. Construction Co. has a 160-acre facility that includes 4200 ft of waterfront along the Gulf Intracoastal Waterway. On the Lake Pontchartrain Causeway project, this waterway access gave the company an advantage while constructing complete safety shoulder segments. The components were cast and assembled at the facility, and then loaded onto self-propelled modular transporters (SPMTs), which were rolled directly onto barges. The assemblies were erected from the barges using SPMTs and without impacting travelers on the causeway. All Photos: Boh Bros. Construction Co. LLC.

The long history of Boh Bros. Construction Co. is rare in the construction industry and is a testament to their commitment to New Orleans and southeastern Louisiana. The company's longevity is also a reflection of its management, according to Jeff Plauche, senior vice president of preconstruction and development. This family-owned company has lasted from generation to generation thanks to a philosophy of service to the community, customers, and coworkers.

In the wake of Hurricane Katrina in 2005, it was all hands on deck, 24 hours a day, to restore the Interstate 10 (I-10) twin spans over Lake Pontchartrain that had been broken into pieces by the storm surge. Boh Bros. employees worked on emergency repairs to the bridge, despite their own personal losses. Plauche says, "We try to maintain our reputation of honorably serving our communities." That devotion to the local community was validated as Boh Bros. worked to help restore New Orleans to its former glory. The rapid response also foreshadowed their penchant for alternative project delivery methods.

"We try to maintain our reputation of honorably serving our communities."

Family Values

Boh Bros. considers their employees part of the family. "That is what makes us unique," says Plauche. More than a century ago, the Boh family started a company based on integrity and a "steady as she goes" philosophy. "We are conservative in our thinking and believe in doing the right thing. Our reputation for a high degree of integrity is paramount."

That attitude has been perpetuated over the years across a workforce whose members often stay with the company for their entire careers. "Funding sources may change and the industries we perform in may vary, but the way we do business never changes," says Plauche.

Although there is tremendous turnover in the construction industry, that is not the case here. Boh Bros. has always been privately held and some years ago started an employee stock ownership plan to recognize the people who are critically important to the success of the company and to reward their loyalty.

Aerial view of the marine deck span installation of the Lake Pontchartrain Causeway, showing tugboats holding the barges in place while the self-propelled modular transporters complete the installation. The new designated breakdown areas address both traffic and safety concerns and were a much-needed addition to the structure. When the bridge was first completed in 1956, the annual traffic count was 200,000; now the bridge carries 12 million vehicles per year.

Gulf Coast

With strong ties to the gulf region and their auspicious beginnings in New Orleans, Boh Bros. has performed thousands of projects in the area and continues to seek out opportunities close to home. Staying local benefits employees, who can return to their families after work. Building in the region also reinforces the company's areas of expertise. They have extensive knowledge about the intricacies of working along the Gulf Coast. South Louisiana soils are very tricky, and working along multiple waterways presents challenges of variable water depths and weather conditions that can affect construction.

Boh Bros. has invested in their own equipment and typically self-performs 85% to 95% of their work. They have the option of using their own casting yard or partnering with local precasters for bridge components. In addition to Boh Bros.' own precast concrete fabrication shop, the New Orleans operations yard also contains a safety training facility, carpentry shop, piling and marine facilities, and equipment and material storage, and has direct barge access.

Now a major player in bridge construction in the region, Boh Bros.' expertise expanded from municipal and road work to pile driving and bridge work. Their portfolio evolved as their in-house experience grew. The interstate highway program drove much of that expansion, as did the development of the power industry. "As the entire industrialized world evolved, we did too," explains Plauche. The area south of Baton Rouge, La., is considered a coastal environment and is conducive to concrete bridge construction. As concrete girder technology has developed and longer spans have become more common, concrete can be considered in more long-span project solutions.

The evolution of Boh Bros.' expertise came with experience in the many and varied concrete structures that cross the Louisiana waterways. In all, Boh Bros. has completed three projects on I-10 over Lake Pontchartrain. After their stellar performance in 2005 on the emergency repairs, they completed one of the two contracts for construction of the elevated I-10 twin spans that are in use today (for details, see the article in the Spring 2011 issue of *ASPIRE*®). Recently, they were awarded another major project: Working for the Greater New Orleans Expressway Commission, they completed a $55 million upgrade to construct new safety shoulder segments along the Lake Pontchartrain Causeway, the longest bridge in the United States.

CMAR Solutions

Boh Bros. served as the construction manager at risk (CMAR) for the Lake Pontchartrain Causeway project, which included constructing twelve 1008-ft-long safety shoulders, or "safety bays," along the existing bridge alignment.

The CMAR approach expedited the design and planning stages and allowed the project team to resolve key challenges and minimize project risk. Throughout the process, Boh Bros. collaborated on constructability, schedule, and budget to help guide the design. In less than nine months, the project moved from preconstruction to construction, a process that typically takes much longer.

Traffic was a primary consideration. To minimize traffic disruptions, the team opted for precast concrete piles, pile caps, and deck span modules that were manufactured off site. The monolithic deck span modules, or safety bay sections, are composed of a concrete deck and traffic barrier cast onto AASHTO girders at the Boh Bros. facility. With this strategy, lane closures were minimized, simplifying

The Lake Pontchartrain Causeway piles and precast concrete pier caps awaiting installation of the precast concrete shoulder assemblies. The safety shoulder segments were supported by one hundred ninety-two 54-in.-diameter precast concrete piles ranging from 54 to 112 ft in length.

In 2005, Hurricane Katrina tore apart sections of the Interstate 10 twin spans over Lake Pontchartrain. After resurrecting five miles of downed causeway pieces and making emergency repairs in less than 29 days to get one of the bridges reopened, Boh Bros. was awarded the contract for the new, more resilient trestle portion of the Interstate 10 twin bridges.

construction sequencing and greatly reducing inconvenience to the public. The completed safety bays provide a safe haven for stranded motorists to pull off the causeway.

Boh Bros. was a critical part of the preconstruction process and their engineering background enabled the team to provide sound constructability input. Plauche says, "We have a built-in appreciation for how changes impact design. That better enables us to suggest construction solutions that work for both the contractor and designer, maximizing benefits to the owner."

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The team procured advance work packages, expediting items that were approved for fabrication before 100% design completion. Before the construction contract was executed, a test pile program was initiated, as was the production of precast, pretensioned concrete girders and concrete cylinder piles. Boh Bros. was ultimately awarded the construction contract, and the company guaranteed the maximum price and schedule duration.

The safety shoulder modules were constructed in an assembly-line process at Boh Bros.' waterfront construction facility, increasing safety and quality. All deck span modules were assembled off site, with precast concrete girders delivered to the yard and a composite deck applied, before the completed units were barged to the bridge.

The CMAR team mentality was critical to the decision to do as much work as possible from the water instead of from the bridge deck. Risk mitigation for the traveling public, cost risk, and safety risk were all addressed before construction started.

Waterside Construction

The most impactful decision for the causeway project was to incorporate accelerated bridge construction (ABC) techniques and fabricate the bridge deck span modules off site, then transport them by barge to the bridge from the Boh Bros. facility. The ABC approach enabled pile driving and precast concrete pile cap construction to be performed concurrently and facilitated construction exclusively using marine equipment. With the piles and caps in place, the crew barged the completed deck units to the site.

"In order to have as little impact on the traveling public as possible, we came up with the modular scheme to install sections coming up from the waterside," explains Plauche. "Using self-propelled modular transporters on barges allowed us to set the completed deck sections with many motorists unaware we were ever there." The creative project solution was recognized by awards from the Associated General Contractors of America and PCI (PCI 2021 Best Rehabilitated Bridge Award).

"The causeway project is one of the best stories we can tell in the CMAR environment," says Plauche. "We listened to the commission staff, the designer, Volkert, and the owner's representative, Huval & Associates, and truly acted as one team. We met their expectations and exceeded their goals. I know it sounds cliché, but that is the definition of building a project with the least disruption to all stakeholders."

Company of Builders

Plauche sees the CMAR project delivery method as the next step in the company's evolution. "In the future, we see Boh Bros. doing what we do best, employing more innovative methods. We are a company of builders. Many field supervisors have come up through the craft ranks, growing our technical and construction expertise."

Project delivery methods have been slow to change in Louisiana. The traditional design-bid-build approach is a good fit for typical everyday projects, but for those projects with high levels of complexity, multiple stakeholders, or potential funding issues, it makes sense to move toward design-build, CMAR, or construction manager/general contractor project delivery methods.

"We have always helped our clients as a team member working for the good of the project, not adversarial or self-serving," says Plauche. "These collaborative procurement methods are a natural fit for us and have allowed us to win more projects in the region since their adoption."

As a contractor that performs much of their own work, Boh Bros. can apply years of experience and lessons learned to enhance the owner's experience. "This is how projects should be done. We want to be a builder and integral project team member, not considered just another bidder," explains Plauche.

Jobsite Technology

With fewer skilled workers to fill the demand, construction companies have to do more with less time, less money, and fewer people. Boh Bros. has adopted innovative methods to mitigate the shortage of skilled laborers in the overall workforce and on their jobsites. In the past, they were able to overcome challenges with huge groups of skilled craftsmen. But with the current and future limits of skilled labor, they have turned to technology and finite level planning. "While our workforce has decreased in number, they have increased in technical ability," explains Plauche.

"We have embraced technology, especially how we communicate among ourselves and with our customers. We are always looking for new ways to make it easier for people in the field." Using technology for field collaboration, Boh Bros. makes use of drones, rugged tablet computers, and ProCore construction management software. "Instead of the old roll of plans, everyone has up-to-date information, just-in-time, all the time," emphasizes Plauche. Being able to share daily logs, photos, comments, and requests for information, and providing clients access to that information, makes all the difference.

"Instead of the old roll of plans, everyone has up-to-date information, just-in-time, all the time."

In-House Expertise

With an in-house engineering and constructability group comes the means to quickly solve shoring, rigging, and other issues that can arise on site. While many of their competitors outsource this service, Boh Bros. has long maintained their own engineering staff. "Our engineering team knows our strengths and capabilities, and the preferences of our field personnel. They can communicate quickly and work to provide custom solutions. I don't know anyone else in the area who does it that way," says Plauche.

Safety First

Inside knowledge of preferred methods also helps Boh Bros. with their safety record and minimizes their need to develop new techniques for every project. "Everything we do starts with a focus on safety. By planning for safety first, the quality results, productivity, and efficiency follow," says Plauche.

"We prioritize the safety of the traveling public and our own people's safety, and everything flows from that," he adds. Statistically, 2020 was the safest year in the company's long history. Civil construction was deemed an essential industry, and Boh Bros. continued work unabated despite COVID-19 restrictions.

"During the pandemic, we were able to keep all of our people working," says Plauche. "Despite another layer of safety planning, we were quick to adapt and keep workers safe and healthy. The challenges posed by the pandemic helped combat complacency and reinforced existing strategies."

Boh Bros. has worked for the past century to complete projects while staying dedicated to the team environment. Plauche says, "While we can share a thousand pictures of bridges throughout our rich history, we want to emphasize our future moving forward with innovative project delivery methods and technology."

Boh Bros. Construction Co.

Boh Bros. Construction Co. is a family-owned, third-generation construction company based in New Orleans, La. Their work includes heavy civil construction, piling, marine, utilities, paving, and site work. Since 1909, the company has had a lasting impact on the bridges and byways that connect the Gulf Coast. They demonstrate that building infrastructure not only supports commerce and commuters but also is the backbone of the community.

The family name is ubiquitous with construction in the New Orleans metropolitan area. Through the decades, Boh Bros. has weathered the good times and the bad, transforming the state's bridge system, constructing the Ernest N. Morial Convention Center, and completing numerous post-Hurricane Katrina repairs, including rebuilding the Interstate 10 twin spans. Through their commitment to quality work and public involvement, the company has earned the respect of its peers, clients, and community.


At 30 ft high, the deck for the new Interstate 10 twin-span bridge is 21 ft higher than the original bridge. Lower-level connections between the super- and substructures are designed to resist uplift forces caused by waves. The new bridge was built with high-performance, high-strength concrete that is more resistant to saltwater corrosion than conventional concrete, and which is expected to provide a 100-year service life (for more details, see the article in the Spring 2011 issue of *ASPIRE*®.)

Diversity, Equity, and Inclusion

How recent social justice movements can have a positive effect on the construction industry

by Drew G. Burns, Slag Cement Association

Recent events in the United States have prompted various social justice movements to address racial disparities within our nation's systems and institutions. These movements, regardless of personal opinions, are ushering in a demand for more transparency from those in power. The American Society of Association Executives' *ASAE Handbook of Professional Practices*[1] includes a list of management trends to watch, which includes the following: "The need for organizational transparency will generate growing demand for information on the ethical implications of the organization's decision-making process."

Although they may not seem directly related to construction, these recent movements provide an opportunity to consider how creating an inclusive work environment will help maximize our industry's potential. As more members of the Baby Boomer generation retire, the industry is dealing with more jobs to fill and a shrinking talent pool. It is important now more than ever to consider expanding the industry's diversity and inclusion initiatives—in part, to help widen that talent pool. Beyond the bottom-line reasons for incorporating these types of programs, regularly having conversations about diversity and inclusion issues will help foster an environment of openness with team members, which has been shown to improve productivity and employee retention.

According to a 2020 report from the U.S. Department of Labor's Bureau of Labor Statistics,[2] the 2019 demographics of the labor force were white, 77%; Black, 13%; and Asian, 6%. The report also includes a breakdown by ethnicity, noting that 18% of the labor force were Hispanics/Latinos, who may identify as one or more races; in this case, 89% of Hispanics/Latinos reported as white. Occupation and industry breakdowns show that more than 30% of Hispanic/Latino workers were employed in jobs associated with production, transportation, materials, natural resources, construction, and maintenance. In contrast, just 21.9% of Black workers were employed in these fields, a statistic that highlights an opportunity to expand hiring efforts in this community.

Because diversity, equity, and inclusion (DEI) is a tough and even controversial subject, many shy away from the topic. However, doing so does not help fix the disparities marginalized groups face. As these conversations become more common, and in turn easier, they often help maximize the effectiveness of organizations and increase the engagement of team members.

Sharing a common terminology is helpful when framing discussions of ethics and social justice. Diversity Best Practices has published an extensive glossary of terms,[3] including the following terms and definitions:

- **Diversity**: Psychological, physical, and social differences that occur among any and all individuals.
- **Equity**: The guarantee of fair treatment, access, opportunity, and advancement while at the same time striving to identify and eliminate barriers that have prevented the full participation of some groups.
- **Inclusion**: The act of creating environments in which any individual or group can be and feel welcomed, respected, supported, and valued to fully participate.
- **Implicit bias:** Negative associations that people unknowingly hold about a group of people or individual, expressed automatically and without conscious awareness. [We all have them; you are not without bias!]
- **BIPOC:** An acronym for Black, Indigenous, and People of Color. The term is meant to acknowledge that not all people of color face the same levels of injustice.

A helpful analogy used many times is that diversity is like being invited to the party; inclusion is like being asked to dance. Inclusion focuses more on who is respected, expected, and integrated into a group, as opposed to just being there. To maximize output, it is critical to pull together different perspectives to find the best way to get things done.

Supporting DEI initiatives in our industry helps avoid discrimination for all marginalized populations. Some types of discrimination include:

- disability,
- race,
- sexual orientation,
- gender,
- age,
- education level, and
- income level.

Creating a DEI plan or incorporating an ethics policy should be a consideration for every organization. Fortunately, the construction industry has many resources available, and initiatives have already started. Many companies have incorporated aggressive DEI programs that can serve as great case studies. Now is the time to start looking at these resources, implement what works for our communities, and share our successes and failures.

Industry associations are hubs for relevant information and resources on these subjects and should be leaned on regularly. Organizations like the ASAE[4] and the Council of Engineering and Scientific Society Executives[5] have plan and policy templates available to download. In the last several years, communities of practice groups like the Women in Concrete Alliance and Associated General Contractors

EDITOR'S NOTE

This article on diversity and inclusion as it relates to workforce development is outside the range of topics usually covered in ASPIRE®. However, we felt that a perspective on this topic may give value to our readers. Members of National Concrete Bridge Council (NCBC) work with the broader construction industry and bridge specifiers who are part of federal, state, and local agencies. The Slag Cement Association, the members of NCBC, and public and private employers engaged in the bridge community are getting more involved in diversity, equity, and inclusion initiatives. After reading this article, please look for resources and guidance in your local area and consider, as the author states, "incorporating these types of programs [by] regularly having conversations about diversity and inclusion issues that will help foster an environment of openness with team members." We present this article as a call to action, to do the right thing by expanding the industry's diversity and inclusion initiatives, and thus make our industry more welcoming to a wider range of our population, providing opportunities to develop and use the talents of many who may not have previously considered working in our bridge industry.

of America's Diversity and Inclusion Council have been working to provide resources and further initiatives in their respective fields. Advancing Organizational Excellence, a consulting firm with association and corporate clients in our industry, offers a proprietary benchmarking tool as well as training and plan resources specifically for the design and construction marketplace.[6]

The construction industry is a unique sector where we combine science, design, natural resources, and community planning. While it may sometimes be uncomfortable, we would be doing ourselves a disservice by not being a part of the conversation to understand how DEI issues impact our workforce. These social movements, and in turn how we collectively respond, will impact the people within our industry.

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Perspectives on Structural Behavior and Redundancy:
Load Path Redundancy

by Dr. Oguzhan Bayrak, University of Texas at Austin

EDITOR'S NOTE ON STRUCTURAL BEHAVIORS SERIES

Robustness, redundancy, resiliency, and ductility of concrete bridges are being discussed by Dr. Bayrak in a series of Perspective articles that began in the Summer 2020 issue of ASPIRE®. *This series is seen by* ASPIRE *as an important discussion for the concrete bridge community as it begins to consider new materials. These new materials have properties that differ significantly from conventional materials, which may lead to different element behavior. For example, some of the new materials exhibit ductile behavior, whereas others do not. These differences require new approaches to design, but the framework necessary for establishing these new design approaches is not clearly defined by current design specifications.*

It should be noted that not all potential failure modes considered in the American Association of State Highway and Transportation Officials' AASHTO LRFD Bridge Design Specifications *are ductile failure modes, so ductility should not be considered as the only criterion for acceptable bridge designs. For example, concrete breakout failure for embedded anchors is quite brittle, which is recognized in calibration of the applicable equations in the AASHTO LRFD specifications. Furthermore, a more complete understanding of the actual capacity of a bridge is provided when the system-level robustness is considered. Different types of redundancies are inherent in concrete bridges, such as load transfer between girders; these contribute to the overall robustness of the bridge by providing multilayer protection against sudden failure. However, quantifying the contribution of these redundancies is not easy. Current AASHTO LRFD specifications have simplified bridge design by considering only element behavior. Therefore, they do not consider overall system behavior and the redundancies that contribute to it.*

This article, which is the final article in this series, focuses on alternate load paths and structural behavior at all levels, from section- to system-level behavior.

My article in the Summer 2020 issue of *ASPIRE®* initiated a discussion on structural, load path, and internal redundancies. My subsequent articles in the Winter 2021 and Spring 2021 issues focused on various aspects of redundancy, resiliency, and robustness of concrete bridges. This article continues the discussion by focusing on load-path redundancy and structural response at the section, member, and structure levels.

Load-Path Redundancy

Load-path redundancy in bridges is the existence of multiple ways in which applied loads can be transferred to the supports. To facilitate a discussion of load-path redundancy, let us consider a couple of examples, beginning with a scenario involving a three-span continuous post-tensioned bridge. **Figure 1** shows the cross section of this two-cell, post-tensioned concrete box-girder bridge. Although the superstructure was designed to handle a variety of different loads and load combinations, an accidental vehicle strike damaging one of the two cells was not explicitly considered in design.

Let us assume an overheight vehicle striking the bridge would damage all internal and external tendons of one cell at the positive moment region in one of the three spans. In the event of such extensive damage, this bridge would benefit from the high torsional strength and stiffness that the undamaged cell possesses. In the damaged span, one-half of the superstructure would be supported as a cantilever from the undamaged cell and use an alternate load path that would aid in the transfer of the weight of the damaged portion,

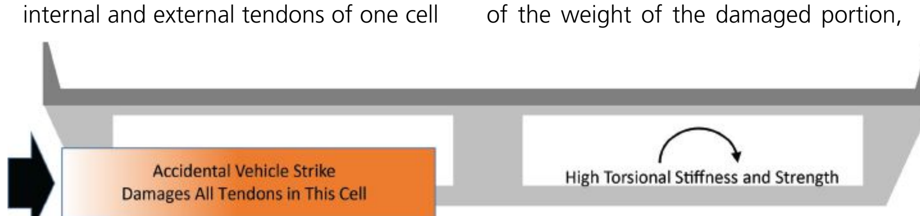

Figure 1. If one cell of a two-cell, three-span continuous post-tensioned concrete box girder is extensively damaged, the bridge would benefit from the high torsional strength and stiffness of the undamaged cell and continuity in the longitudinal direction. Figure: Dr. Oguzhan Bayrak.

Figure 2. Severe damage to a two-cell, post-tensioned concrete box-girder bridge from an overheight vehicle strike. The stiffness of the remaining box-girder superstructure prevented structural collapse. Photo: Kansas Department of Transportation.

and any loads placed on it, into the supports. Although this bridge was not designed to accommodate such a loading scenario, a vehicle strike would likely not result in collapse. The alternate load path is facilitated by continuity in the longitudinal direction, by the well-distributed post-tensioning layout, and by the torsional stiffness and strength of the undamaged cell.

Figure 2 shows an example similar to that described in Fig. 1; in this example, the boom of an excavator that was being transported by truck severed the great majority of the longitudinal reinforcement near a support. In this case, the stiffness of the box-girder superstructure as well as the concrete bridge rail served to mobilize alternate load paths that prevented structural collapse.

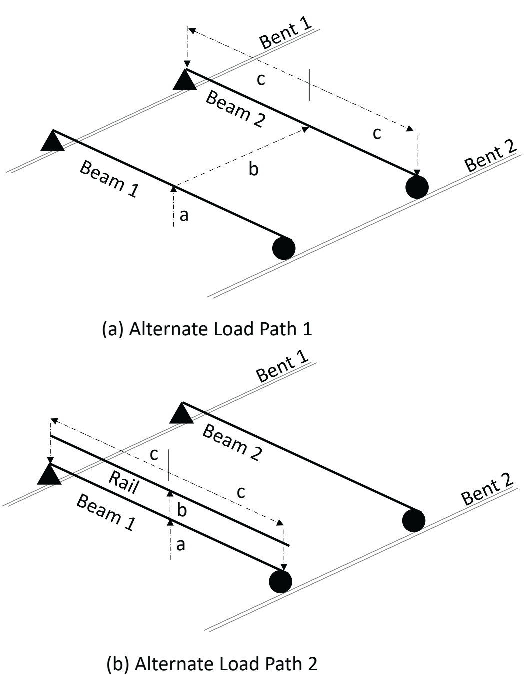

Figure 4. As a result of redundancies, two alternative load paths are available after a fascia girder, represented in the figure as beam 1, is heavily damaged near midspan. Figure: Dr. Oguzhan Bayrak.

In the next example, let us consider a precast and prestressed concrete girder bridge with the deck supported on four girder lines. The simply supported span was damaged by an overheight vehicle strike, severely damaging the bottom flange and web of the fascia girder (**Fig. 3**). The adjacent girder was damaged to a lesser extent. **Figure 4** illustrates two alternate load paths that likely helped the bridge survive the vehicle strike and associated damage that was not explicitly considered in the original design.

Alternate load path 1 (Fig. 4a) requires the deck to work as a cantilever to pick up the load (from the location marked as "a" in Fig. 4a) that was originally supported by the fascia girder (beam 1) and transfer it to beam 2 (along the path marked as "b" in Fig. 4a). Beam 2 subsequently carries the load to bents 1 and 2 (using the paths marked as "c" in Fig. 4a). Alternate load path 2 (Fig. 4b) involves the overhang portion of the deck taking the load (from the location marked as "a" in Fig. 4b) that was originally supported by the fascia girder (beam 1) over to the bridge rail (along the path marked as "b" in Fig. 4b). The bridge rail now works as the new fascia girder carrying the load to bents 1 and 2 (along the paths marked as "c" in Fig. 4b, although the load may also go back into the girder and into the supports at undamaged locations). In reality, the load will be shared by a combination of both of these alternate load paths. The member that displays the larger stiffness will attract a greater portion of the load that was originally carried by the fascia girder.

Undoubtedly, the distribution of forces is a function of material strengths as well as the bridge geometry—for example, beam spacing, girder depth, and bridge rail geometry. Depending on the aforementioned factors, the rail may play a more or less important role compared to the slab cantilevering to pick up the load. Having acknowledged that subtlety, we must recognize two important points. First, bridge decks are never designed for this type of loading.

Figure 3. Severe damage to a prestressed concrete beam bridge caused by an overheight vehicle strike. Load-path redundancy within the multibeam system prevented collapse. Photo: Mark Bloschock.

The reinforcement details, use of partial-depth precast concrete panels, and the like, are all controlled by applicable service and strength limit states of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[1] However, when called upon, the top and bottom mat reinforcement in the deck will serve to reinforce the cantilever to transfer the load. Second, bridge rails are designed for vehicle impact, and their design purpose is to keep vehicles on the bridge. To meet their intended design function, the rails are crash-tested to verify their design. Once again, when the need arises, as it does in this vehicle-strike scenario, the rails can serve as a substitute for the fascia girder and provide an alternate load path, even when the rails are jointed.

In summary, a bridge's actual behavior is dictated by the structural details provided in that bridge. For example, in the aforementioned case, deck reinforcement that is primarily intended to resist cracking caused by volume changes due to temperature and shrinkage can readily serve as flexural reinforcement in a cantilever. There is no replacement for good structural details, robust reinforcement detailing, and good conceptual designs.

Section-, Component-, and System-Level Responses

Previous articles in this series focused on the relationship among the sectional response, the response of a potential plastic hinge, and the member-level response. We also examined the influence of structural redundancy on overall response. The previously discussed overheight vehicle strike cases provide the framework for our thinking regarding primary (intended) and secondary (alternate or backup) load paths in cases where unexpected conditions challenge a bridge's ability to support permanent and applied loads. The presence of primary and secondary load paths results in a robust structural response where a concrete bridge can make use of a variety of different load paths under different loading or damage scenarios. Ultimately, the system-level response is the most important. With that said, there are a variety of ways to obtain an abundantly redundant concrete bridge system displaying a robust structural response. The cases discussed previously provide good examples of robust structural response where local damage was contained and did not progress into structural collapse.

The AASHTO LFRD specifications were calibrated using a reliability-based methodology to ensure a reasonably uniform level of component safety. For typical concrete bridge systems ranging from simple to complex, there is a relationship between the component-level and system-level responses. In a reliability-based framework, accurate capacity estimations with minimal statistical bias, both for load and deformation capacities, will lead to better estimations at the system level.

The importance of minimizing statistical bias cannot be overemphasized. Engineers are typically predisposed to making decisions on the safe side, and understandably so. In many cases, and especially within the context of behavioral failure modes at the element level, this approach is easy to follow. If one decides to play on the safe side for every step of the evaluation moving from a cross section to a plastic hinge, then to a component, and finally to the system level, an accumulation of conservative assumptions may introduce considerable statistical bias in estimating the system-level response.

Alternatively, and as was done in the AASHTO *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges,*[2] a more systematic approach aimed at minimizing statistical bias and targeting appropriate levels of reliability (as measured by reliability index β) for the inventory (design) rating ($\beta = 3.5$) and operating (load rating) rating ($\beta = 2.5$) can be used. Concepts underpinning the philosophy adopted in the AASHTO LRFR, and later in the AASHTO *Manual for Bridge Evaluation*,[3] are discussed in many publications. Weed[4] provides a concise discussion of this topic. There are a number of additional guidance documents that acknowledge and implement a reliability-based framework to load rate concrete bridges. For example, the Florida Department of Transportation commissioned studies to establish rational load-rating procedures for their segmental and spliced girder bridges.[5,6]

Implementation of System-Level Behavior

The preceding discussion describes how our design and load-rating specifications have recognized the importance of structural, load-path, and internal redundancies for quite some time. Next, let us explore an example that demonstrates the implementation of these concepts in our specifications, such as the load rating of segmental bridges (See the Spring 2021 issue of *ASPIRE* for an article on load rating segmental bridges.). **Table 1** shows that the system factor ϕ_s, in this case for post-tensioned segmental concrete box-girder bridges, is a function of several variables, including the bridge type and construction method. In effect, the system factor is intended to reflect the presence of alternate load paths and give credit to more-redundant structural systems. The second column shows that the determinacy (structural redundancy) influences the system factor, with the third column explicitly indicating the reasoning. For example, a statically determinate span needs to form one hinge to establish a collapse mechanism; an end span of a continuous unit needs to form two. (For details on plastic hinges, see the article in this series in the Winter 2021 issue of *ASPIRE*.) With respect to internal redundancy, as seen in the last columns of the table, as the number of tendons in each web increases, so does ϕ_s. Furthermore, the impact of this redundancy on ϕ_s is quite significant and is nonlinear, as can be

Table 1. System factors for single-cell, post-tensioned segmental concrete box-girder bridges

Bridge type	Span type	Number of hinges to failure	System factors (ϕ_s)			
			Number of tendons per web			
			1	2	3	4
Precast balanced-cantilever, Type A joints	Interior span	3	0.90	1.05	1.15	1.20
	End or hinge span	2	0.85	1.00	1.10	1.15
	Statically determinate	1	n/a	0.90	1.00	1.10
Precast span-by-span, Type A joints	Interior span	3	n/a	1.00	1.10	1.20
	End or hinge span	2	n/a	0.95	1.05	1.15
	Statically determinate	1	n/a	n/a	1.00	1.10
Precast span-by-span, Type B joints	Interior span	3	n/a	1.00	1.10	1.20
	End or hinge span	2	n/a	0.95	1.05	1.15
	Statically determinate	1	n/a	n/a	1.00	1.10
Cast-in-place balanced-cantilever	Interior span	3	0.90	1.05	1.15	1.20
	End or hinge span	2	0.85	1.00	1.10	1.15
	Statically determinate	1	n/a	0.90	1.00	1.10

Note: For box-girder bridges with three or more webs, table values may be increased by 0.10. Adapted by Dr. Oguzhan Bayrak from references 2, 5, and 6.

expected from a complex bridge. Finally, and importantly, the system factors listed in the table were developed for a single-cell box. In cases where there are three or more webs (that is, two cells or more, or two box girders), the values in the table can be further increased. This last fact is driven by the load-path redundancy introduced by additional webs. While this table was specifically developed for post-tensioned segmental box-girder bridges, similar trends in the system factor could be expected for pretensioned concrete multigirder bridges, although such a table has not yet been developed.

Conclusion

Structural indeterminacy, load-path redundancy, and internal redundancy serve as three layers of robustness for concrete bridges. All three types of redundancies have been discussed in this series of articles. The discussions covered a wide range of topics, including the theoretical background and definitions, the design framework employed in the AASHTO LRFD specifications, and real-world examples. As illustrated in this article, the presence of all types of redundancies leads to alternative load paths and gives concrete bridges multiple lines of defense in the event they are subjected to extreme events. Bridge designers should also resist the inclination to include too many conservative assumptions into the design of components or elements in an attempt to improve the redundancy or robustness of the whole bridge. Attempting to enhance the redundancy or robustness of a bridge system by introducing more and more conservatism into the design of individual components or elements will not necessarily achieve the desired levels of redundancy or robustness.

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PERSPECTIVE

The Digital Twin Evolution

Ask the Experts: Digital Twin Technology for Bridge Design, Construction, and Beyond

by Monica Schultes

This article explores the burgeoning world of digital twins and how they could revolutionize the transportation infrastructure industry. It delves into defining this technology and its potential effect on planning, design, and construction of concrete bridges.

Digital twin technology can create a virtual "as-built" replica of a physical object such as an actual bridge. In addition to the benefits this technology provides during design and construction, owners can monitor their valuable asset throughout its life cycle and can predict maintenance needs or improve future designs.

Although the concept of a digital twin has been around since 2002, it has only recently become cost effective to implement, thanks to the internet of things. A digital twin requires three parts: the physical structure, the virtual model, and the connection between the two. It is the continuous connection between the structure and model that distinguishes digital twin technology from building information modeling (BIM).

We asked experts from ALLPLAN Infrastructure, Bentley Systems, and Eriksson Software to discuss how digital twin technology will shape the industry and how digital twins of bridges are making the transition from idea to reality. Responses have been edited for length and clarity.

Q: What is your definition of "digital twin"?

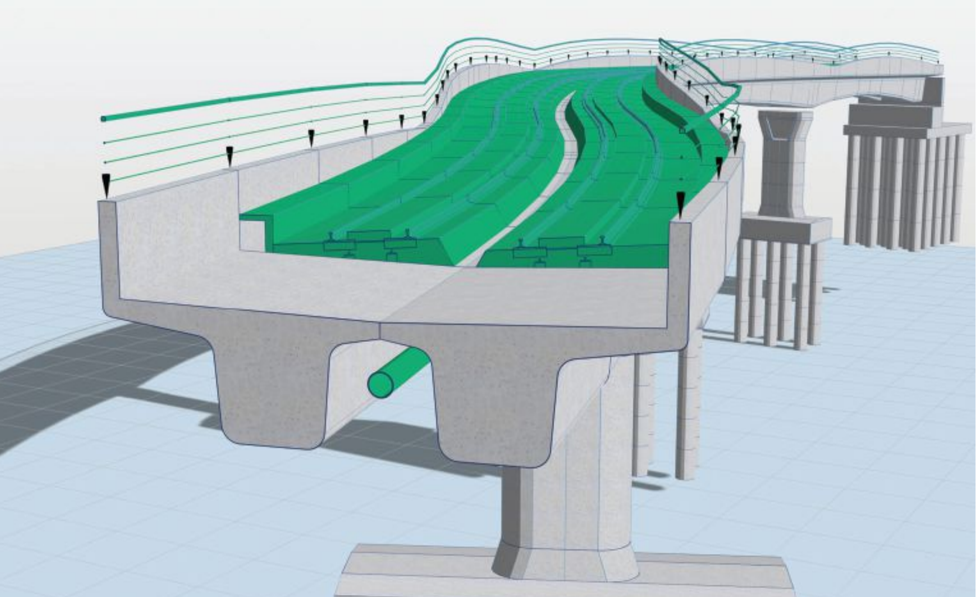
A: **ALLPLAN:** We like to refer to the digital twin as a digital replica of construction that helps us to better understand the future. During the design phase, the digital twin simulates how the structure will look and feel. During construction, it monitors the schedule and budget in real time. Finally, through the operation phase, the digital twin monitors how the bridge is performing and anticipates any maintenance.

BENTLEY: The definition we like to use is that a digital twin is a digital representation of a physical asset or system that is integrated with engineering information that allows us to understand and model its performance. A digital twin combines data from continuous surveys, photogrammetry, lidar [light detection and ranging], and sensors. It tracks changes along a timeline, allowing owners to view the digital representation of the asset and the real-world conditions over time. A 3-D [three-dimensional] model is like a snapshot, but the digital twin is like the living, breathing representation of the bridge. It provides the ability to see information beyond the design and construction stages.

Are digital twins a natural evolution from BIM?

ERIKSSON: The digital twin is an extension of BIM but goes further by accommodating more detailed information and with a broader scope. We are changing the way things are done in the design environment. Instead of separate processes for design and drafting, the BIM modeler works in concert with the structural engineer to design and detail a structure and its component parts. They analyze and detail and populate the model. Right now, our work ends at the BIM model. There are still some who print out 2-D drawings and those who are looking to convert to CNC [computer numerical control] machine processes or 3-D printing. BIM is a subset of the twin. You can't have a twin without BIM.

Allplan Bridge and Allplan Bimplus use parametric bridge design and detailing with structural analysis. These platforms store bridge models in an object-based database. Figure: ALLPLAN Deutschland GmbH.



A three-dimensional model is like a snapshot, whereas a digital twin is like a living, breathing representation of a bridge that allows owners to view a replica of their asset in real-world conditions over time. Figure: Bentley Systems.

What is the future of digital twin technology?

BENTLEY: The potential for digital twins is unlimited. Our iTwin Services enable engineering firms to create, visualize, and analyze digital twins of infrastructure projects. Openness will be a prerequisite for delivering digital twins to advance our industry beyond BIM. One future potential for digital twins is with machine learning. Right now, a large amount of data is collected within the digital twin, due to all the changes and connections among information. Machine learning creates an opportunity to see the lessons learned from a portfolio of projects and identify trends and patterns that resulted in mistakes, cost increases, or safety incidents.

ERIKSSON: About 10 years ago we sensed that technology and the communication infrastructure had advanced to the point where widespread interconnectivity among stakeholders in the design process was in sight. BIM was taking hold in our industry. In 2015, we completely redesigned our data framework to enable us to integrate with a fully connected world. We pivoted to staking our future on project delivery via BIM and fully committed to supporting this technology. Our workflow now connects design to a BIM model in a two-way fashion. We developed our technology in the commercial market and are now moving that technology to the bridge market. Because of our extensive planning, there will be no loss of data integrity or fidelity in this transition.

Are there project examples?

BENTLEY: We worked with Foth Infrastructure & Environment to establish a 3-D model as a digital twin, with data flowing to and from the model, as field personnel identified and resolved potential issues on site. The digital twin enabled stakeholder review and buy-in, ensuring that the project was well communicated to the community. Beyond construction, the engineering data contained in the digital twin will provide value to future operations. New York State DOT [Department of Transportation] is taking advantage of technology and moving to model-based design and digital twins. They utilized OpenRoads and OpenBridge to solicit bids in their first-ever model-based contracting project: Route 20. Using digital twins enabled digital review that, compared with traditional print and scan methodology, allowed contractors to access data from the 3-D model on their tablets and easily get elevations.

What are the biggest challenges facing adoption of this technology?

ALLPLAN: 2-D drawing-based methods demonstrate just how error-prone these processes can be, but they are a fundamental part of engineering culture. BIM makes the most sense when the models are used by everyone and thus presupposes that all organizations involved are willing to optimize their processes together. It is a huge challenge to transform an entire industry, especially as paper drawings are still a robust way to get information to a site where sun, rain, mud, thieves, and missing internet connectivity are just some of the challenges for the users of mobile devices.

ERIKSSON: The biggest challenges to adopting this new technology are the lack of software, awareness, and training, as well as the change in traditional methods and workflows. Another hurdle is handling the massive amount of data generated from multiple sources during the bridge design and construction phases.

What are the biggest rewards to stakeholders?

ALLPLAN: The biggest reward to stakeholders is that digitalization through BIM improves quality and saves time and money. Those gains are realized through improved communication and optimized data management during the asset's life cycle. But it is not that simple. We always talk about the technology itself. But it

EDITOR'S NOTE

ASPIRE® *was introduced to the concept of digital twinning in a presentation by David H. Parker at the Structural Health Monitoring Subcommittee (AKT40[3]) meeting during the 2021 Transportation Research Board Annual Meeting. The presentation discussed the digital twinning concept and how it could be used for bridges. The FIU Pedestrian Bridge collapse was used as an example to highlight that the concepts of digital twinning could have been used to provide diagnostic measurements that could have been useful for identifying the structural issues prior to the collapse.*

This article is a brief introduction to digital twinning, and a second article, which will include perspectives from David Parker, is planned to further explore the application of the concept to bridges and how engineering judgment is essential to evaluate conditions and changes when implementing digital twin technology.

An unmanned aerial vehicle (drone) captured high-resolution images that were used to create a reality mesh linked to a digital twin for the restoration of the James J. Hill Stone Arch Bridge project in Minneapolis, Minn. Software from Bentley Systems was used to create the digital twin. Photo: Bentley Systems.

is not only the technology that makes things happen. A very important aspect is the human factor. Within the design process of any structure, many different experts are involved. The number of people involved and the necessity for their collaboration rises with the complexity and scale of the project. The technology is important, because if certain workflows are not established, then there is no collaboration. The platform we have established supports the complete design cycle and, due to our open BIM approach, the exchange of data is streamlined.

ERIKSSON: While it is a huge undertaking, for twin technology to succeed, there have to be immediate benefits to the stakeholders. Efforts to date have fallen short because there needs to be a 20% savings to the design engineer to have the incentive to drive it forward. With Eriksson Sync technology, we are seeing a 25% reduction of the labor for design and detailing of precast concrete, and once you can meet that threshold, the benefits outweigh the learning curve. The success on commercial projects has proven that it [the technology] does help reduce costs and increase accuracy—we have seen a near elimination of errors. Communication is more seamless and real time and unambiguous with the Sync system. Those benefits could also be realized on bridge projects.

How do you think this will transform the industry?

ERIKSSON: Digital twin technology could transform the industry with better collaboration, improved accuracy, better data integrity (it never goes out to paper and then gets scanned back in), error reduction, broader and deeper knowledge about the structure, better record keeping and record accessibility, accelerated fabrication, and improved construction schedules—better results for all stakeholders.

ALLPLAN: Bridges extensively fitted with sensors could facilitate a reliability-optimized maintenance management of bridges. But it is still the construction process where knowledge-based design systems can help to plan and build ever better bridges that realize savings in time and budget.

Conclusion

Digital twin technology is charting a path to reduce design costs, increase accuracy, and improve communication. However, there are several challenges to widespread adoption. Digital twin technology requires time and skilled resources. Because it is so new to the industry, many companies do not yet have this expertise, which leads to the next challenge: money. The initial investment may take several years to recoup. The corporate culture of the industry is slow to adopt new technology, and digital twins are no different. Lastly, lowest-cost project delivery and the fragmented organization of the industry create more obstacles.

Digital twin technology has a lot to offer and now that the technology exists, it will grow and adapt and ultimately change the industry. A

ASPIRE acknowledges the insights and expertise from Meg Davis, industry marketing director, road and bridge, and Mo Harmon, director of industry strategy, design engineering, at Bentley Systems; Roy Eriksson, chief executive officer at Eriksson Software; and Stefan Kaufman, BIM strategy and new technologies, and Gregor Strekelj, product manager infrastructure and authorized representative, at ALLPLAN Infrastructure.

PROJECT

Condition Evaluation of the JFK Causeway Post-tensioned Segmental Bridge

by Brian D. Merrill, Wiss, Janney, Elstner Associates Inc.

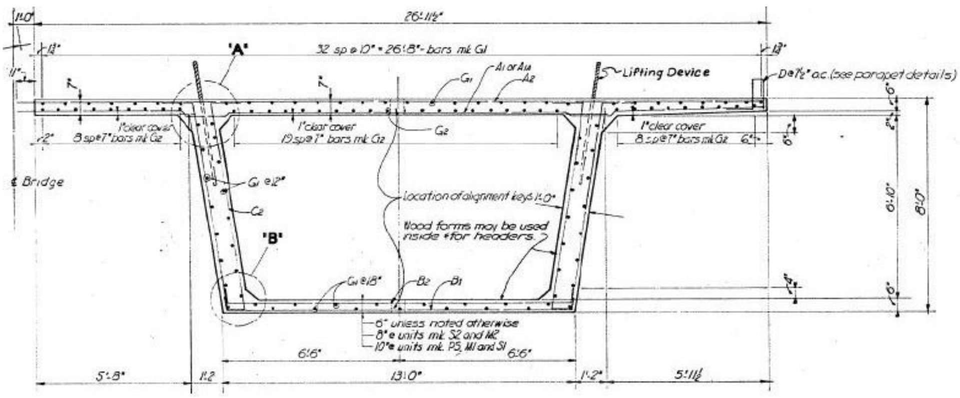
The John F. Kennedy (JFK) Memorial Causeway Bridge, completed in 1973, carries Texas Park Road 22 over the Gulf Intracoastal Waterway (GIWW), connecting Corpus Christi to North Padre Island, Tex.

The original causeway was built in 1950 as a two-lane toll road with swing bridges across two channels. In 1973, it was replaced with a four-lane public roadway that consists of 36 prestressed concrete beam approach spans and a continuous three-span segmental unit over the GIWW. The 3280-ft-long, 60-ft-wide bridge carries two lanes in each direction. The main span continuous unit was the first precast concrete post-tensioned (PT) segmental bridge built in the United States to carry vehicular traffic and was primarily designed by the University of Texas at Austin (UT) with assistance from the Texas Department of Transportation (TxDOT). This article reports on the thorough condition investigation and service-life modeling of the structure that was conducted in 2019 to determine rehabilitation strategies to extend the bridge's service life by at least 25 years.

Research, Design, and Construction

The project started with a TxDOT research project conducted in 1969 by Dr. John E. Breen of UT to identify a viable concrete alternate to structural steel bridges in the 130- to 350-ft-span range. The research project identified concrete PT segmental bridges as a viable candidate based on studies of bridges recently constructed in Europe.[1] TxDOT then extended UT's contract to investigate other design and construction aspects of segmental construction in four subsequent studies: epoxies for segment joints, design and optimization studies, computer analysis, and load tests of a scale-model bridge.[2–5] The studies culminated with a final report, *Minimizing Construction Problems in Segmentally Precast Box Girder Bridges*.[6] The JFK Causeway was actually the second precast concrete segmental

The John F. Kennedy Memorial Causeway Bridge over the Gulf Intracoastal Waterway was completed in 1973. The 400-ft-long (200 ft main span with 100 ft back spans) continuous main unit was the first precast concrete post-tensioned segmental box-girder bridge built in the United States. Photo: Texas Department of Transportation.



Details of the typical box-girder section. Post-tensioning duct locations are not shown. Figure: Texas Department of Transportation (from original construction plans).

The precast concrete segments were erected using balanced-cantilever construction. A custom-designed erection jig was used to hold a segment in place for application of the joint epoxy to the mating faces is visible. Photo: Alan Matejowsky.

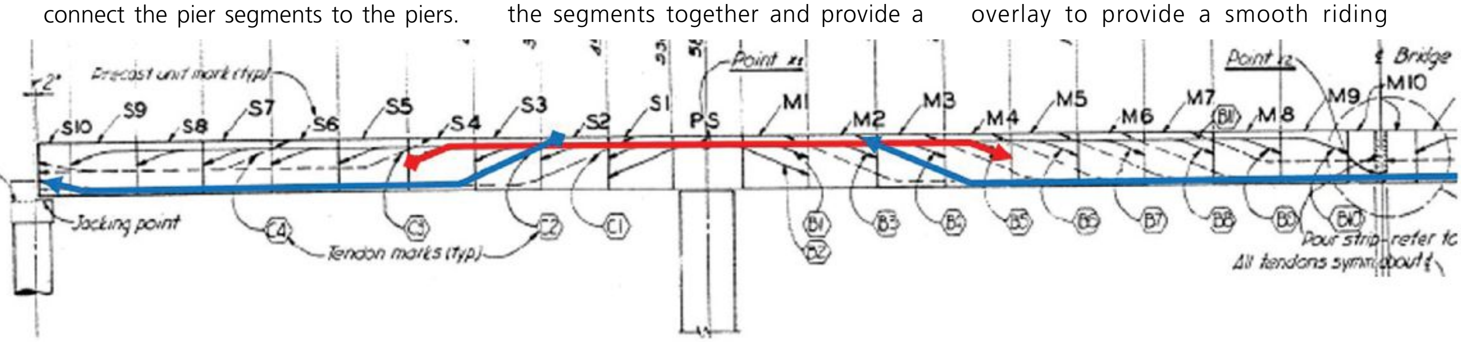
bridge built in the United States; the first was the ⅙-scale model constructed and tested by UT.[5] UT held several meetings with prospective contractors during scale-model construction and testing to help in understanding the challenges to be faced during construction.

The segmental unit has a 200-ft-long main span over the GIWW, with 100-ft-long back spans for a total continuous unit length of 400 ft. The unit consists of a pair of segmental precast concrete box-girder sections that are 13 ft wide at the base, 28 ft 8 in. wide at the wings, and have a constant depth of 8 ft. The bridge is supported by two reinforced concrete columns at each interior pier, with the pier supported on large pile footings. The ends are supported on three-column transition bents.

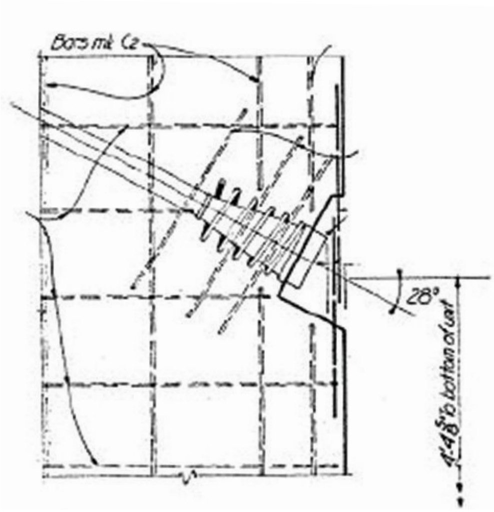
The precast concrete segments were match cast and fabricated by PCI member Heldenfels Brothers Construction Corporation at their Corpus Christi precast yard. The main unit was constructed by first erecting the two 5-ft-long pier segments on top of the reinforced concrete piers and engaging hold-down bars to temporarily connect the pier segments to the piers. The span segments were transported to the site and lifted into position using cranes and a custom-designed erection jig to hold the segments in place for application of the epoxy. The mating faces of the segments were coated with epoxy before joining them together. The epoxy serves as a lubricant when the segments are brought together, and as a permanent joint seal between the precast concrete segments. The span segments were erected on alternating sides of the piers so that the span remained no more than one segment out of balance at all times during construction—a process known as balanced-cantilever construction. The precast concrete segments included large shear keys in each web to transfer vertical shear loads between adjacent segments, and an alignment key in the top and bottom slabs at the box centerline to aid in segment alignment during erection. No permanent moment connection was made between the span and the main piers.

PT tendons, consisting of a varying number of prestressing strands, were inserted through metal ducts cast in the segments (see tendon layout below). The tendons were tensioned to hold the segments together and provide a minimum level of compression over the full cross-sectional area of the box sections under service loads. During segment erection, cantilever tendons in the top slab were used to hold the segments in place as subsequent segments were erected. Once the full complement of segments was erected, a cast-in-place closure pour was made at the middle of the main span. Continuity tendons were then inserted into metal ducts that extended from the deck down into the bottom of the box segments to produce a fully continuous structural unit. The pier hold-down bars were then released and abandoned. The cantilever tendons were anchored in the box webs near the large shear keys. The continuity tendon anchors were located at the ends of the unit and in the top slab.

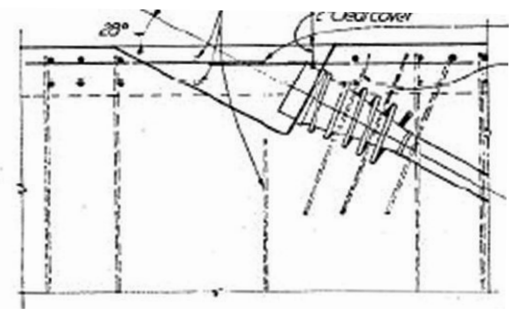
The bridge design for both the approach and main spans did not include any of the corrosion mitigation provisions that are typically employed in modern designs for similar marine-exposure locations, such as high-performance concrete, epoxy-coated or other corrosion-resistant reinforcing steel, or additional concrete clear cover to the embedded reinforcement. The segmental unit's original design included a 1½-in. asphalt overlay to provide a smooth riding



Post-tensioning tendon layout schematic for half of the bridge. The red line indicates a typical cantilever tendon, and the blue line indicates a typical continuity tendon. The main span continuity post-tensioning tendons have varying numbers of strands. Figure: Texas Department of Transportation (original plans) with annotation by Wiss, Janney, Elstner Associates Inc.



Cantilever tendon anchor in web.



Continuity tendon anchor in deck.

Typical post-tensioning anchor details as shown in original plans. Figure: Texas Department of Transportation.

surface, but no overlay was provided for the prestressed concrete beam approach spans. In the 7-in.-thick segment top slabs, the design clear cover was 1⅛ in. for the top mat of reinforcing steel and 1 in. for the bottom mat. For the 12-in.-thick webs and the 6-in.-thick bottom slab, the interior and exterior clear covers were both 1½ in.

Condition Assessment

In November 2019, a condition assessment of the main span continuous unit was performed. It included the following tasks: visually assessing 100% of the interior and exterior of both box sections; locating PT ducts using nondestructive evaluation methods to identify potential grout anomalies (for example, voids); opening selected tendons or anchorages for visual inspection and grout sampling; coring at various locations on the box girders for chloride and carbonation testing; using ground-penetrating radar to survey reinforcing bar cover; and performing half-cell corrosion potential testing. The goal of the assessment was to develop repair recommendations for a target service-life extension of at least 25 years.

Deck tendon after excavation and opening of ducts for inspection.

Continuity tendon anchor in deck exposed for inspection.

Borescope image of small void in deck tendon near post-tensioning anchor.

Moderate corrosion of continuity tendon anchor at end of box girder.

Photographs from the condition assessment of the main span continuous unit that included visually assessing 100% of the interior and exterior of both box girders; locating post-tensioning (PT) ducts using nondestructive evaluation methods to identify potential grout anomalies; and exposing selected tendons or anchorages for visual inspection and grout sampling. The PT tendon survey indicated that the PT system was generally in very good condition. Photos: Wiss, Janney, Elstner Associates Inc.

Spalling on the exterior face of the box girder exposed corroded supplemental (not indicated in original plans) wire-mesh reinforcement with insufficient clear cover. Photo: Wiss, Janney, Elstner Associates Inc.

The exterior visual survey identified diagonal cracking in the webs that had occurred during tensioning of the cantilever tendons and had been sealed with epoxy, spalling in the pourback mortar at the end anchorages of the continuity tendons, and isolated surface spalling with exposed reinforcing steel. No distress was observed at the previously sealed web cracks, and spalling that exposed corroded reinforcing steel occurred only at locations where it appeared that supplemental (not indicated in the plans) wire-mesh reinforcement had been installed with insufficient clear cover.

The visual survey of the interior of the box girders revealed diagonal cracking at the diaphragms in the pier segments, web cracking reflecting the cracks on the exterior face of the webs, and some evidence of moisture intrusion at the deck anchorages. An important observation was that no segment joint had any evidence of leaking.

The PT tendon survey indicated that the PT system was generally in very good condition. Very few grout voids were detected, and the strands that were uncovered in the deck or box web ducts were in like-new condition. There was some evidence of regrouting, likely to fill voids left during initial grouting. No evidence of PT system distress was observed, except for moderate corrosion of the end anchors where the pourback concrete failed to protect them from the corrosive environment. No distress was observed to be associated with the moisture intrusion at the deck anchorages. It was apparent that great care had been taken during construction to ensure the ducts were fully grouted.

Chloride ingress was evaluated at several locations on the bridge: top of deck, underside of wings, inside and outside webs, and the bottom slab. Chloride concentrations for all cored locations were well below the corrosion threshold at the level of the reinforcing steel. Clear cover of the main reinforcing steel was uniform across the box sections with little variation, except for the previously mentioned supplemental steel and isolated miscellaneous steel pieces left in the forms.

Conclusion

The condition data and the clear cover measurements were used to develop an in-house service-life model, which indicated that the structure could easily attain a 25-year service-life extension with the following treatments:

- Replacement of the asphalt overlays using a waterproofing membrane or with a polyester polymer concrete overlay
- Spot repairs to the isolated corrosion spalling
- Addition of a water-repellant coating to the exposed box-girder surfaces
- Replacement of the pourbacks at the end tendon anchorages
- Possible addition of a cathodic protection system to the substructure

The JFK Causeway Segmental Bridge is in overall good condition considering its marine-exposure environment and the lack of corrosion-mitigating features included in its original design. There were minor occurrences of corrosion, which were mainly related to initial construction defects, but the PT system was in like-new condition.

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***Brian D. Merrill** is a principal in the Austin, Tex., office of Wiss, Janney, Elstner Associates Inc.*

PROJECT

Middlebury Bridge and Rail Project

by Aaron Guyette, VHB; Jeb Pittsinger, Mott MacDonald; and Jon Griffin, Vermont Agency of Transportation

Increasing the vertical clearance for the railroad by more than 3 ft required substantial excavation and shoring. All Photos and Figures: VHB.

Nestled in the heart of the Green Mountains, Middlebury, Vt., is a quaint New England village. It is the shire town (county seat) of Addison County, the home of Middlebury College, and the heart of the region's culture, arts, restaurants, and commercial economy. Winding through the heart of downtown Middlebury runs the former Rutland Railway, now operated by Vermont Railway. Originally constructed in the 1840s, the railroad split the downtown area in half and had two bridges that spanned the 20-ft-deep rail corridor running through the town green. The bridges were replaced in the 1920s but had since deteriorated to the point where their structural integrity was threatening the safety of vehicle drivers, bicyclists, and pedestrians above and the operation of the railroad below.

The Middlebury Bridge and Rail Project was initiated in response to the deteriorating condition of the two almost 100-year-old bridges carrying Main Street and Merchants Row over the Vermont Railway. In addition to the crumbling bridges, the railroad corridor had been plagued by drainage issues, poor track conditions, and vertical and horizonal clearance restrictions. Poor track conditions contributed to a 2007 train derailment, highlighting the critical need for improvements throughout the corridor.

Shared Sacrifice

Solutions had to address both the project location in downtown Middlebury as well as technical requirements for the roadways and railroad. Infrastructure improvements would need to meet not only technical code requirements but also construction requirements dictated by mobility needs, time restrictions, impacts on public spaces, and potential irreparable harm to the historic Middlebury downtown commercial district. The extensive needs of all stakeholders led the project team to pitch a shared sacrifice model. With this approach, the Vermont Agency of Transportation (VTrans) agreed to structure its construction contract for an accelerated bridge construction (ABC) period to reduce the overall construction impact, the operating railroad agreed to allow a 10-week extended track closure, and the Town of Middlebury agreed to a 10-week full closure of its downtown streets—which would essentially cut the downtown community in half.

CMGC Project Approach

The project was structured as construction manager/general contractor (CMGC), where the construction manager was a key member of the design process. Using the CMGC approach enabled the project team to develop a constructable concept that provided certainty in the schedule and helped define impacts to project stakeholders and the general public well in advance of actual construction. Backed with this information straight from the contractor, the project team engaged in a robust public outreach plan to establish local relationships and build credibility in the community. The open communication led to a great working relationship with local government officials and project stakeholders.

The overall general scope of the project called for replacing the bridges and maintaining the existing roadway profiles along municipal streets while increasing the overall vertical clearance for the railroad by more than 3 ft. With no way to build upward, the project team would excavate downward to accommodate the vertical clearance, which resulted in adjustment to the railroad profile for approximately 3500 ft. The project team still needed to identify solutions for railroad drainage, permanent retaining walls, and an ABC approach.

A Precast Concrete Solution

As the project team evaluated structure types, it became clear that a precast concrete box structure was an ideal solution for many design parameters. A concrete box provided a durable, long-term solution that could be quickly assembled as part of the ABC approach. It would permanently retain surrounding soils and support the existing roadways, and it provided a sealed structure that would keep groundwater out and help collect and convey stormwater from the tunnel approaches. As an added

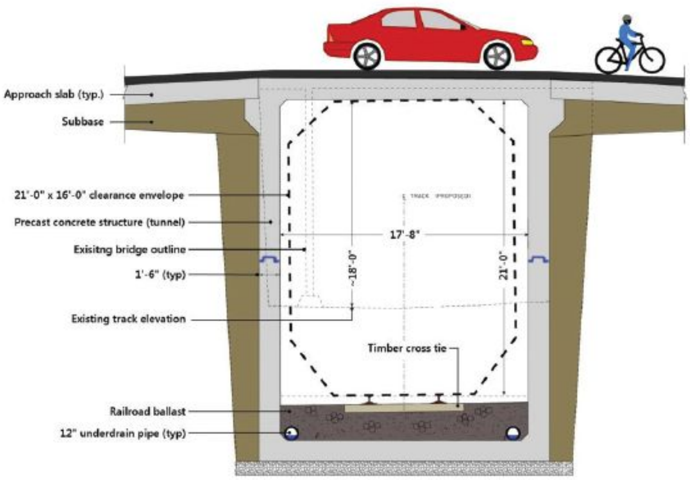
profile

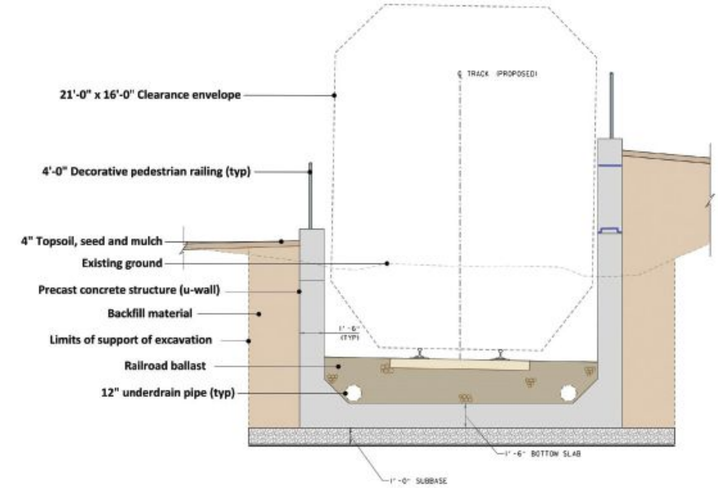
MIDDLEBURY BRIDGE AND RAIL PROJECT / MIDDLEBURY, VERMONT

BRIDGE DESIGN ENGINEER: VHB, South Burlington, Vt.

TUNNEL ENGINEER: Mott MacDonald, Westwood, Mass.

PRIME CONTRACTOR: Kubricky Construction Corporation, Wilton, N.Y.





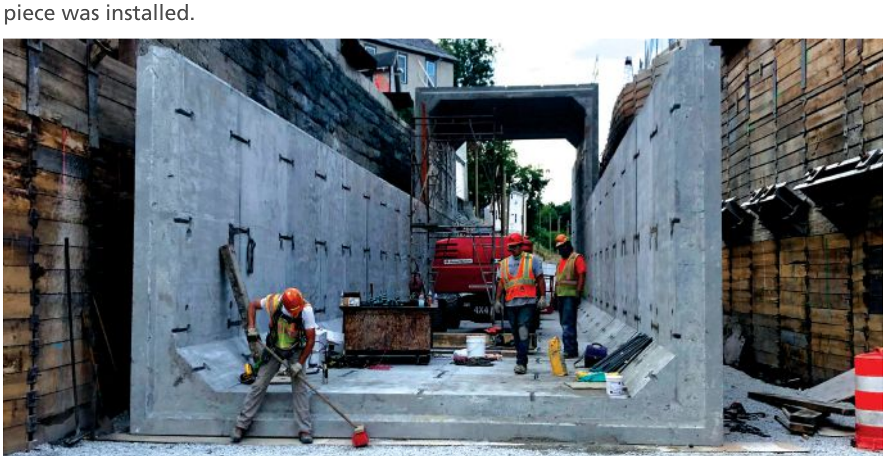
Cross section of two-piece precast concrete tunnel at highway crossing (left). Cross section of precast concrete U-shaped retaining wall (right).

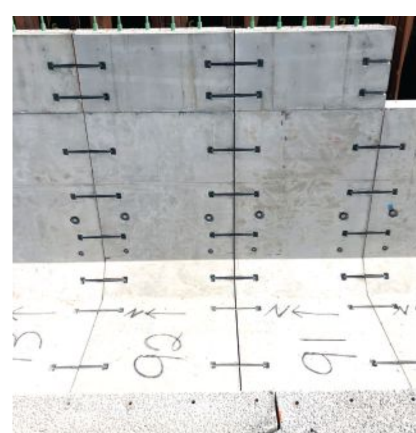
advantage, the box structure could be extended between the two existing bridge locations to create a tunnel and reconnect the historic town green in downtown Middlebury. As design of the concrete box evolved, a two-piece system emerged as the best option because it provided an appropriately sized structure for the tunnel, with dimensions that could be prefabricated off site and transported by truck to the jobsite. The 345-ft-long concrete box consists of a series of bottom U-shapes and top U-shapes that join together with a keyway to form the 24-ft 4-in.-high × 17-ft 9-in.-wide clear opening inside the tunnel. Each tunnel U-shape was cast monolithically; is 7 ft 6 in. long, 13 ft 8 in. high, and 20 ft 9 in. wide; and weighs more than 30 tons. The keyed joint where the top and bottom of the tunnel fit together was modeled as a pin connection, thereby transferring no moment and simplifying connection requirements in the field. The structural design called for 5000-psi concrete compressive strength, and the design team opted to use galvanized reinforcing steel to help protect against deterioration and provide a 100-year service life for the new structure. The individual pieces were connected longitudinally using galvanized "dog-bone" hardware that could be quickly inserted and tensioned before the next piece was installed. After the precast concrete segments were installed, backfill was placed up to the final grade, with compacted granular material used where the width adjacent to the structure was greater than 3 ft, and controlled-density flowable fill used where the width was less than 3 ft.

Using the two-piece precast concrete box tunnel led to the use of U-shaped retaining walls to retain soils outside of the tunnel portals. The walls stretch 323 ft to the south and 1065 ft to the north. The typical monolithic vertical leg of the U-shaped retaining walls is 11 ft tall. Where taller sections were required to retain the fill, precast concrete panels were post-tensioned to the base to extend the vertical wall by as much as 14 ft. Tops of the U-shaped retaining walls were finished with a cast-in-place concrete cap and decorative pedestrian railing.

In total, the tunnel and U-shaped retaining walls consist of 422 individual pieces of precast concrete, all fabricated in upstate New York, trucked to a marshalling yard about a mile from the project site, and then meticulously

Erection and assembly of precast concrete tunnel pieces. The individual U-shaped tunnel segments and retaining walls were connected longitudinally using galvanized "dog-bone" hardware that could be quickly inserted and tensioned before the next precast concrete piece was installed.



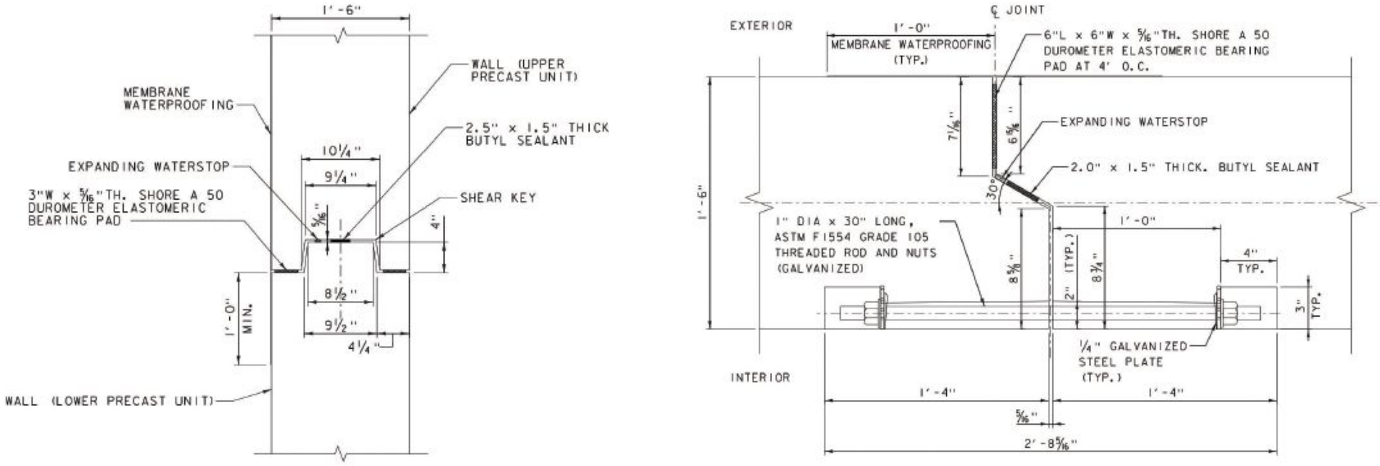


VERMONT AGENCY OF TRANSPORTATION, OWNER

PRECASTER: Fort Miller Company, Schuylerville, N.Y.—a PCI-certified producer

PROJECT DESCRIPTION: 345-ft-long precast concrete railroad tunnel and 1388-ft-long U-shaped retaining walls consisting of 422 individual precast concrete pieces

BRIDGE CONSTRUCTION COST: $62.5 million



Two types of joints were used on this project: keyed longitudinal joints in the walls connecting the U-shaped tunnel or wall sections (left), and shiplap joints for the transverse dog-bone connections between tunnel or wall segments (right). The use of shiplap joints was seen as one of the biggest risks associated with construction.

transported to the jobsite and set in place during the 10-week ABC period in 2020.

Although the overall project lent itself to using precast concrete for the tunnel and U-shaped retaining walls, the team faced significant hurdles to accommodate the required horizontal and vertical geometry of the railroad corridor and to develop a watertight joint configuration for the precast concrete pieces. The profile along the railroad corridor consists of shallow vertical grades descending from both the northern and southern limits of the project to a low point on a vertical curve in the tunnel. The bottom slab of the tunnel was designed with a low point for the gravity conveyance and collection of stormwater that flows through the bottom of the slab and into a new stormwater piping network.

The horizontal alignment of the railroad corridor consists of spiral reverse curves, which were accommodated by chorded segments of the precast concrete U-walls and tunnel. Pieces of precast concrete along each chord were of consistent shape and size, and allowed repetitive forming and fabrication; however, each chord was connected by a specialized transition piece fabricated to turn a small angle to the next chord. Using this approach allowed uniformity in the precast concrete fabrication as well as greater predictability in joint width along the length of the project.

The project team spent a significant amount of time designing, detailing, and practicing the transverse joint construction in the field, which was seen as one of the biggest risks associated with construction. Precast concrete erection started with a single "key" piece at the low point of the tunnel and continued by placing additional pieces north and south. Each piece used a transverse shiplap joint in the precast concrete in combination with elastomeric bearing pads, butyl sealant, expanding hydrophilic waterstops, and self-adhesive membrane. The ideal joint width was 5⁄16 in.; however, the joint width was also designed to be variable up to ¾ in., allowing for slight adjustments to the horizontal alignment of the precast concrete.

Project Construction

Project construction kicked off in the summer of 2017 with an emergency project to demolish the increasingly dangerous existing bridges and erect temporary bridges at the two crossings. Construction continued in the following years with preparations for the main event during the 2020 construction season. These enabling works included installing support of excavation along the project corridor, constructing a series of gravity drainage tunnels through bedrock, and preparing crane pads for setting the precast concrete U-shaped retaining walls and tunnel pieces.

In July 2020, the 10-week ABC period started. Crews worked around the clock for 70 straight days, completing a massive earth excavation, blasting solid rock, setting the precast concrete pieces, backfilling and reconstructing the municipal roadways, and reconstructing the railroad track through the tunnel and U-wall section. Precast concrete pieces were set over a week-long period in late July, with erection rates averaging one piece per hour, including installation of the joint gasket materials, alignment adjustments, and tensioning of connecting bolts. The ABC period successfully concluded ahead of schedule in early September with a ceremonial passenger train and the resumption of regular vehicular traffic.

Conclusion

The project has one more year of construction to complete new sidewalks, landscaping, final paving, and the construction of new public park space. However, the positive impact on downtown Middlebury is already evident with the reconnection of the town green and Triangle Park for the first time in nearly 180 years. The benefits of this project will be evident for generations to come.

Aaron Guyette is transportation market lead and a project manager at VHB in South Burlington, Vt.; Jeb Pittsinger is a senior project engineer at Mott MacDonald in Westwood, Mass.; and Jon Griffin is a structures project manager at the Vermont Agency of Transportation in Barre, Vt.

Ceremonial first train passing through the tunnel and U-shaped retaining walls.

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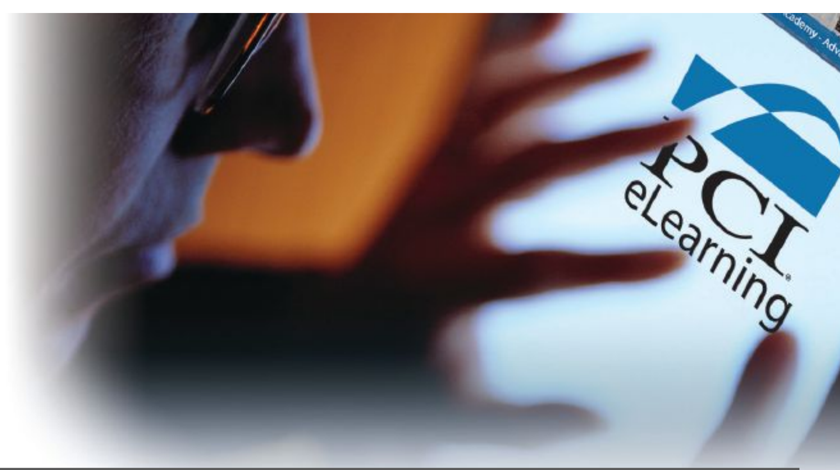

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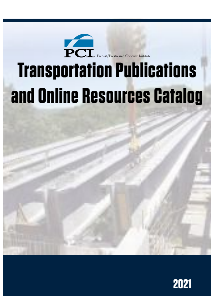

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T100 series course is based on Chapters 1 through 9 of *PCI Bridge Design Manual*, 3rd ed., 2nd release (MNL-133).

T200 series courses are based on the *State-of-the-Art Report on Full-Depth Precast Concrete Bridge Deck Panels* (SOA-01-1911).

T310 series course is based on MNL-133 Chapter 11.

T450 series courses are based on MNL-133 Chapter 10. T710 series course is based on MNL-133 Chapter 18.

T500 and T510 series courses are based on the *Bridge Geometry Manual* (CB-02-20).

T520 series courses are based on *Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders* (CB-02-16) and *User Manual for Calculating the Lateral Stability of Precast, Prestressed Concrete Bridge Girders* (CB-04-20).

T350 series courses are based on the *Curved Precast Concrete Bridges State-of-the-Art Report* (CB-01-12), *Guide Document for the Design of Curved, Spliced Precast Concrete U-Beam Bridges* (CB-03-20), and MNL-133 Chapter 12.

AASHTO THE VOICE OF TRANSPORTATION

PCI Precast/Prestressed Concrete Institute

PROJECT

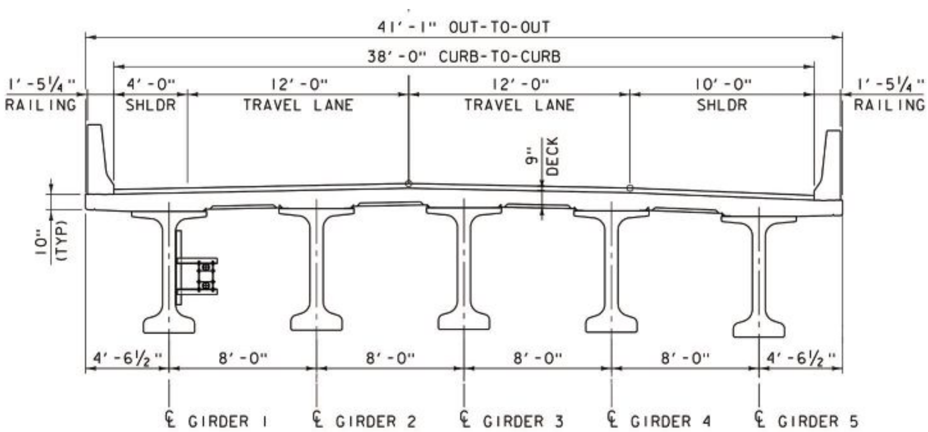
Designing for Resilience and Durability on the Longest Spliced Precast Concrete Girder Bridge in Vermont

by Thomas French, HDR

Interstate 91 (I-91) carries travelers north and south along the scenic banks of the Connecticut River through the "Green Mountain State" of Vermont, from Massachusetts to the Canadian border. Amid the beautiful rolling hills in the southeast portion of the state, the highway crosses a moderate ravine in the town of Rockingham that contains the Green Mountain Railroad and the Williams River.

As part of the interstate highway expansion in the 1960s, the Williams River was relocated to its current location and causeways were constructed north and south of the river. Between 1963 and 1965, twin four-span steel deck-truss bridges were constructed to connect these causeways. The bridges, each nearly 750 ft long, independently carry traffic north and south.

As traffic levels increased over the years, portions of the concrete decks, concrete substructures, and painted steel truss superstructures began to show advanced levels of deterioration. Due to cold New England winters, I-91 is subjected to deicing agents for about six months of every year. At 50 years of service, the bridges exhibited reinforcing steel corrosion in the decks and columns and associated concrete spalling that required regular repair efforts beyond routine maintenance. The Vermont Agency of Transportation (VTrans) undertook an alternatives analysis and determined that a bridge replacement project was warranted.



Cross section of the new northbound bridge in a constant-depth section. The southbound bridge has the same cross-sectional dimensions. All Photos and Figures: HDR.

Citing overall project schedule reduction and the desire for an innovative solution, VTrans opted for a design-build project delivery method. During the bidding period, the design-build team evaluated several alternative structure types, including balanced-cantilever segmental concrete box girders, steel haunched girders, and precast concrete girders. The design-build team ultimately selected precast concrete spliced-girder bridges due to overall project cost, construction methods that matched the contractor's skill set, relative ease of construction, a structure type that exceeded the 100-year service life requirement of the bridges, and the availability of a relatively local precaster that could supply the necessary components of the bridge.

To provide the best solution to achieve the project goals, identical twin structures were constructed in place of the existing bridges. To match the interstate highway corridor, each bridge now provides two 12-ft-wide travel lanes, one 10-ft-wide breakdown shoulder, and one 4-ft-wide median shoulder. Each new bridge is over 41 ft wide, more than 6 ft wider than the existing bridges.

Project Requirements and Local Challenges

The request for proposals for the design-build project included several important criteria to ensure the replacement bridges

profile

INTERSTATE 91 BRIDGES 24N AND 24S / ROCKINGHAM, VERMONT

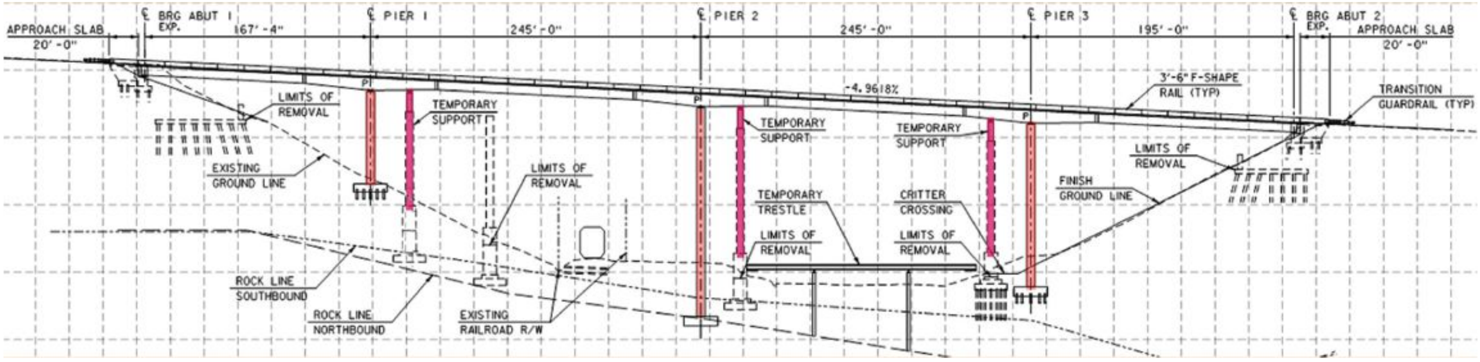
BRIDGE DESIGN ENGINEER: HDR, Omaha, Neb.

ERECTION ENGINEER: McNary Bergeron & Associates, Tampa, Fla.

PRIME CONTRACTOR: Reed & Reed Inc., Woolwich, Maine

PRECASTER: J. P. Carrara & Sons Inc., Middlebury, Vt.—a PCI-certified producer

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



Elevation view of the new bridges showing temporary girder support locations and the temporary work platform.

would meet the needs of VTrans and the traveling public throughout the structures' service lives.

Span Configuration

The bridge concept could include any span configuration, as long as piers did not impede the riverbanks more than the existing bridge, or encroach on the railroad right-of-way envelope. To accomplish this, the design-build team proposed a four-span structure with identical 245-ft-long main spans and unsymmetrical end spans with lengths of 167 ft 4 in. and 195 ft, respectively, resulting in a completed bridge length, including closure pours, of just over 860 ft. The proposed bridge was 110 ft longer than the existing bridge as a result of eliminating two 45-ft-long vaulted abutments and constructing the new abutments behind the existing abutments to avoid pile conflicts. This particular span layout allowed the contractor to use the existing piers 2 and 3 as temporary supports during girder erection.

Hundred-Year Life Expectancy

The structures must have a life expectancy without a significant rehabilitation event for a minimum of 100 years. The design team developed conceptual design details for each major component of the bridges, and those details were evaluated by corrosion specialists to determine the time to initial corrosion period and the propagation period, the sum of which result in the time to first repair. The team balanced concrete cover and mixture proportions with appropriate reinforcing material types to achieve major bridge elements that met the required life expectancy in an aggressive deicing environment. **Table 1** lists the major bridge elements and their respective requirements for concrete design strength, reinforcing bar material type, concrete cover, and requirements for corrosion-inhibitor admixture.

Pier Slenderness Ratio

Understanding that the replacement bridges would have very tall piers, VTrans wanted to ensure resiliency by limiting the pier slenderness ratio, kL/r, to no greater than 80, where k is the effective length factor, L is the unsupported length (height), and r is the radius of gyration. The intent of the slenderness ratio limit was to create a less flexible pier system with a lower susceptibility to cracking, thus increasing resiliency. To maintain a competitive bid price for the project, the design-build team needed to use pier forms that the contractor already had. This requirement locked in the cross-sectional shape of the piers. With the height of the piers set to match site constraints, and the radius of gyration

Table 1. Major bridge element criteria to meet 100-year service life requirements. Black bar was used for portions of elements not listed.

	Structural element	Design concrete strength, psi	Mild reinforcement material	Concrete cover, in.	Calcium nitrite corrosion-inhibitor admixture
Superstructure	Precast concrete girder	9000	Black bar*	1.75	Yes
	Precast girder, stirrups	9000	Stainless steel†	1.00	No
	Barrier (inside face)	4000	Stainless steel†	1.50	No
	Deck slab (top)	4000	Stainless steel†	2.50	No
	Approach slab (top)	3500	Epoxy-coated‡	2.50	Yes
	Girder splice CIP closure	9000	Black bar*	1.75	Yes
Substructure	Pier footings	3500	Black bar*	3.00	Yes
	Pier shaft	3500	Black bar*	5.50	Yes
	Pier cap	3500	Stainless steel†	4.00	No
	Abutment stems exposed face	3500	Black bar*	3.00	Yes

*AASHTO M 31M/M 31: *Standard Specification for Deformed and Plain Carbon and Low-Alloy Steel Bars for Concrete Reinforcement.*

†ASTM A955/A955M: *Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement.*

‡ASTM A775/A775M: *Standard Specification for Epoxy-Coated Steel Reinforcing Bars.*

VERMONT AGENCY OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: Twin 863-ft-long, four-span post-tensioned precast concrete spliced-girder bridges

STRUCTURAL COMPONENTS: Seventy modified NEBT-79 precast, prestressed concrete girder segments, 30 of which were haunched to 10 ft deep; 9-in.-thick cast-in-place concrete deck with stainless steel reinforcement and galvanized stay-in-place deck forms; cast-in-place concrete pier caps, columns, footings, and abutments on steel H-piles

BRIDGE CONSTRUCTION COST: $50 million

AWARDS: PCI 2021 Design Award, Best Bridge with a Main Span More Than 150 Feet

A haunched girder segment after being lifted off the delivery vehicle parked on the existing truss bridge. An in-depth analysis of the existing bridge demonstrated that it was safe to have the new girder segments on the existing structure as long as there was no other traffic on the bridge at the same time.

Piers for the northbound bridge during construction. To maintain a competitive bid price, the design-build team used pier forms the contractor already had.

and the height set by the cross section, the only variable the design team could work with was the effective length factor. Understanding that a traditional single bearing per girder would yield an effective length factor of 2.0 due to the transitional and rotational freedom that occurs in that configuration, the design team proposed an innovative two-bearing-per-girder design. This design resulted in rotational resistance at the top of the pier based on the relative stiffness between columns and girders that resulted in an effective length factor less than 2.0.

Constructing the Longest Spliced Precast Concrete Girder Bridge in Vermont

To span the ravine with four spans, each of the five girder lines comprises seven precast, prestressed concrete Northeast bulb-tee (NEBT) girder segments. Segments 2, 4, and 6 are identical and are haunched to sit on the piers. To construct the haunched girder segments, the precaster started with a standard NEBT-79 form but excluded the bottom form. The precaster custom made two variable-depth bottom forms to transition the bottom flange height from the standard 8.7 in. to 49.9 in. to provide the desired haunched depth. Each haunched segment weighs 93.5 tons (187,000 lb), is 96 ft long, and varies in depth from 10 ft at the pier to 6 ft 6¾ in. at the ends. Segments 1, 3, 5, and 7 are all 6 ft 6¾ in. deep and are 120 ft, 145 ft, 145 ft, and 147 ft 4 in. long, respectively, with the longest segment weighing 88.3 tons (176,600 lb).

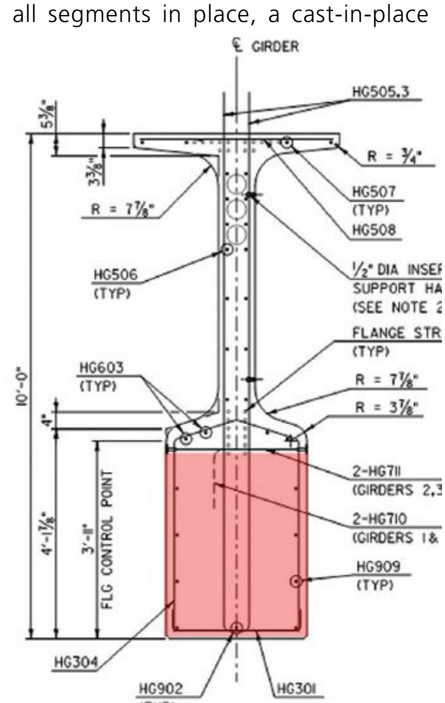
The girder segments were fabricated only 96 miles away in Middlebury, Vt., but, due to site constraints, they had to be taken off the delivery vehicle from the existing bridge. An in-depth analysis of the aged existing bridge was performed, and it was deemed safe to have the new girder segments on the existing structure as long as there was no other traffic on the bridge at the same time. The contractor deployed a rolling roadblock that slowed highway traffic down, allowing for a 20-minute window in which to hook up a girder segment to a crane and lift it from the delivery vehicle.

The segments were erected by first placing the haunched girder segments over the piers. Before delivery to the site, each segment was fitted with two 24 × 24 in. reinforced elastomeric bearing pads. The segments were then lifted over their respective piers and placed on temporary supports that left an approximately 1 in. space below the bearings. The segments were surveyed, and the proper profile was set by adjusting the temporary support jacks. Once the segments were in the correct location and profile, high-strength nonshrink grout was placed to create the permanent plinth under the bearing pads. This procedure was undertaken to maximize bearing installation flexibility because the tolerance of bearing elevation pedestals was less than 1⁄16 in. By leaving the bearings floating while alignment adjustments were made, the bearings could be set without introducing any permanent rotational displacements.

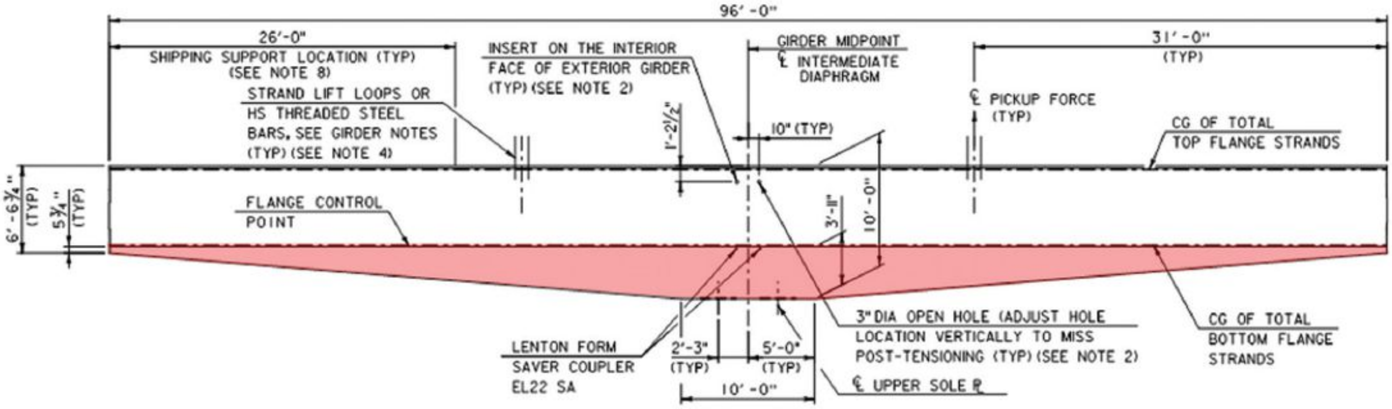
After the haunched girder segments were installed, the drop-in and end girder segments were added systematically and temporarily hung from the haunched segments using temporary steel strongbacks. With all segments in place, a cast-in-place

Table 2. Pier slenderness ratio for design

	Pier 1	Pier 2	Pier 3
Effective length factor *k*	1.900	1.177	1.265
Height of column *L*	86.4 ft	128.1 ft	117.5 ft
Radius of gyration *r*	27.7 in.	27.7 in.	27.7 in.
Slenderness ratio *kL*/*r*	71.12	65.24	64.37



Cross section of haunched Northeast bulb-tee girder segment at the pier. Concrete section added to achieve haunch is shaded.



Elevation view of the haunched Northeast bulb-tee pier segment. Each haunched girder segment varied in depth from 10 ft at the pier to 6 ft 6¾ in. at the ends and weighed 93.5 tons (187,000 lb). Concrete section added to achieve haunch is shaded.

closure diaphragm was constructed from exterior girder to exterior girder at each segment joint. After all of the diaphragms were cast and the concrete cured, each of the girder lines was post-tensioned with three bonded tendons containing nineteen 0.6-in.-diameter low-relaxation strands. The girders were post-tensioned from each end of the bridges, resulting in a 2079 kip total tensioning force in each girder.

Conclusion

Using the first precast concrete spliced-girder bridges in Vermont, the project's design provided an economical solution for this important transportation link. Key to that design is an all-concrete structure that incorporates pretensioning, post-tensioning, and a blend of reinforcing materials, allowing local suppliers to provide the necessary materials to ensure the required 100-year service life. The northbound bridge opened to traffic in April 2019 and the southbound bridge was expected to open in June 2021.

Thomas French is a senior project manager with HDR in Manchester, N.H.

Construction of the southbound bridge superstructure with the completed northbound bridge in the background.

AESTHETICS **COMMENTARY**

by Frederick Gottemoeller

Attractive bridges use their shapes to illustrate how they work: they are thick where the forces are the greatest, and thin everywhere else. People can intuitively understand the reasons for their shapes, and this understanding results in a positive feeling of engagement and satisfaction.

Because the efficient use of materials is an engineering criterion that encourages the use of such shapes, in theory it ought to be easy for engineers to produce attractive bridges. Unfortunately, engineering economy often gets in the way. Standardized shapes or bridge elements are less expensive because they are easier to produce, not because they embody the most efficient use of materials. Thankfully, engineering efficiency and engineering economy all came together in the Rockingham, Vt., Interstate 91 bridge project, and the result is structures that are efficient, economical, and elegant.

Let's start with the piers. Design requirements for a stiff pier plus the contractor's prior ownership of the forms encouraged a simple, tapered shape with an elegantly proportioned cap. Simplicity is underrated as an aesthetic characteristic, and this pier is about as simple as it can be. It's thickest at the bottom, where the overturning moments are the greatest; it gradually narrows toward the top, as the forces decrease; and then it widens to accept the girders.

The girder is thickened over the pier, which, in addition to accommodating the forces concentrated there, matches the intuitive understanding that there are forces concentrated there. The thickening is accomplished by the simplest method possible: tapering the bottom flange of the girder.

That's it. No other rustications or embellishments are present. No other rustications or embellishments are needed. Yet Vermonters will be able to take pride in these bridges for 100 years to come.

Rendering of the precast concrete spliced-girder bridges in Rockingham, Vt.

Threading a Needle

Rolling gantry system safely speeds installation of longest-ever precast concrete girders in Mississippi

by Sam Barnes, Barnes Media LLC

Because of the slope of the roadway and the skew of the bents, the self-propelled modular transporters needed to be repositioned each time a girder was set. Photo: Barnhart.

Key Constructors' megaproject on Interstate 20 (I-20) resembles central Houston, Tex., more than the south side of Jackson, Miss., given the number of bridges, service roads, and on-ramps in the vicinity. The contractor is threading a needle as it replaces a deteriorated section of the I-20 eastbound bridge with a larger 14-span bridge at the confluence of I-20 with Interstate 55 (I-55) and U.S. Highway 51 (U.S. 51).

Much of the project team's early attention, however, was on the $42.2 million project's biggest hurdle: the three-span section of bridge needed to cross a stretch of rail owned by CN railroad. Addressing this hurdle would eventually require the placement of the longest precast concrete girders in Mississippi's history, seven of them reaching 170 ft in length and weighing 200,000 lb each.

In November 2019, Key Constructors president Jason Henry asked Mike Cassibry, the sales manager for Barnhart Crane & Rigging, to visit the site and possibly find a workable solution. This proved to be a wise move. After a series of brainstorming sessions among Key, Barnhart, and engineering consulting firm Huval & Associates, the team developed an innovative rolling gantry system using self-propelled modular transporters (SPMTs) that could easily handle the massive girders while minimizing impacts on traffic and safely eliminating the need for a work trestle or shoring of existing bridges.

Same Equipment, Different Application

The use of SPMTs is nothing new. In fact, many states are beginning to plan accelerated bridge construction projects that will include SPMTs for a variety of uses. (see the Focus article in this issue of *ASPIRE®,* where the use of SPMTs for the Lake Pontchartrain safety shoulder project is discussed).

At the I-20 site, however, the team came up with a decidedly different application. During girder erection in late 2020, Barnhart used two pairs of SPMTs to support twin gantry cranes across the new bridge site, situating two SPMTs on the existing I-20 westbound bridge and the other two on U.S. 51. The SPMTs moved longitudinally along the existing bridge decks to precise positions while spreading the girder loads to the bridges' superstructures below.

The SPMTs were also able to easily manage the varying elevation of the bridge decks caused by longitudinal and transverse changes in grade. Cassibry, now a Key Constructors project manager, says Barnhart engineers worked with Huval & Associates to model the operation and "performed some number crunching" to ensure it would meet structural capacity limitations of the existing bridges and provide adequate load stability.

Some tweaks were made along the way. The project team had originally planned to use supportive stands on the SPMT decks to achieve the necessary heights, but that method would not have provided adequate stability. "The

Barnhart R&D Department suggested that we integrate standard shipping containers into the system," says John Engberg, Barnhart's vice president of engineering. "By stacking the inexpensive containers on top of the SPMTs, we achieved the perfect height … and they're 8 ft wide, so they're very stable."

The 20-ft-long cargo containers sat directly on top of the SPMT platforms and decking, and were secured by container corner beams (fabricated by Barnhart in Memphis, Tenn.) and ¼-in. chains.

"It's a simple solution, for sure, but we're not building rocket ships," Engberg says. "We're trying to come up with solutions that will do the job. That also allowed us to accommodate the uneven road surfaces. The road wasn't flat, so as we were going from one span to the next the roadway was sloping up and down. That meant we had to move our system down each time we set a girder because of the way they were skewed."

The team also chose to "decouple" the SPMT pairs so that they could reposition each pair independently. Not all of the massive bridge girders were the same length, so the spacing between the SPMTs had to be adjusted when going from one span to the next. "Originally, we had all four Goldhofers [SPMTs] tied together," says Matt Scrip, Barnhart project manager. "I was a bit nervous about that, because it would have required a significant amount of coordination. If one started to outrun the other, it could have put a lot of torque into the system."

The team left a lane open on U.S. 51 (which was shut down) so that girder delivery vehicles could park immediately adjacent to the SPMTs. "We would lift [girders] off of the trucks and start sliding them across to set them," Scrip says. "It was critical for the girders to be delivered in the right orientation. They were so long, and the jobsite was so congested. … If they showed up in the wrong orientation, it would have been problematic to say the least."

Barnhart field superintendent Rick Umfress coordinated closely with

Interstate 20 Flyover Bridge

by Natalie McCombs, HNTB

In February 2017, the Mississippi Department of Transportation (MDOT) hired HNTB to perform a value-engineering study on Interstate 20 eastbound bridge no. 44.9B at Interstate 55 (I-55) South in Jackson, Miss. At that time, the proposed plans showed a 1784-ft-long bridge with a maximum span of 360 ft. Steel welded-plate girders with web depths of 80 and 144 in. were proposed. HNTB's study revealed two significant improvements that would save costs for the project. The first improvement was to reduce the 360 ft span over I-55 using cast-in-place concrete straddle bents at a few key locations along the alignment. The use of straddle bents allowed optimization of pier locations and 150 ft spans. The shorter spans made standard 78-in.-deep prestressed concrete Florida I-beams (FIB) sections a feasible option for most of the bridge. The second improvement was to reduce the 280 ft span over the railroad to 170 ft from center to center of pier. That span was now governed by a reduced horizontal clearance requirement established by CN railroad, which allowed a pier to be placed on the railroad right-of-way rather than requiring a clear span of the entire right-of-way.

Even with the shorter span, the standard FIB-78 beams would not be the best structural solution. Instead, 168-ft-long FIB-84 beams were used. They were the deepest and longest precast concrete beams used in Mississippi to date, and they weighed around 200,000 lb. The contractor used an innovative approach that involved self-propelled modular transporters to set these long, heavy beams over the railroad corridor. By implementing the improvements specified in the value-engineering study, the 1855-ft-long bridge costs were reduced by $20 million and a durable concrete structure was provided for MDOT.

Aerial view of the two pairs of self-propelled modular transporters (SPMTs) with gantry system, and the 170-ft-long, 200,000 lb girders. Using the SPMTs minimized lane closures. Photo: Barnhart.

Engineers analyzed the existing bridges to ensure that they had sufficient structural capacity to support the self-propelled modular transporters and the massive girders during the erection operation. Photo: Key Constructors.

The first 170-ft-long, 200,000 lb girder after it was erected over the railroad. Photo: Key Constructors.

Key, the railroad, and other team members before and during the lifts, meeting with them at the beginning of each day to go over job safety and plans for the day.

Vital to the Critical Path

After only about a week and a half of setup, the team was erecting six girders a day, with each girder lifted directly off the transport vehicle, moved transversely, and set on the bearing pad within 30 minutes of delivery. In 10 days, all 21 prestressed concrete girders were placed and the rolling gantry system was moved to the laydown area for disassembly.

Trent Holbrook, the Mississippi Department of Transportation engineer who oversees projects in the area, says Barnhart's rolling gantry system was critical to keeping the project on track for October 2021 completion. It also alleviated traffic impacts by minimizing lane closures and disruptions.

"That area is tight," Holbrook says. "And the railroad had lots of restrictions for working in the right-of-way, vibrations, etc. Otherwise, some rather large cranes would have been necessary to lift and place these 200,000 lb beams."

Once complete, the new bridge will handle both east- and westbound I-20 traffic, and the existing I-20 West bridge will be used solely for I-55 traffic. The I-55/I-20 merger is also being moved farther to the east. "Essentially, we're tearing down one I-20 span, and the other span will become part of I-55," Holbrook says. "We're on schedule and should finish with the deck placement in July, followed by the completion of the rails and asphalt approaches to the bridge."

Sam Barnes is a freelance writer with Barnes Media LLC in Baton Rouge, La. Natalie McCombs is an associate fellow and senior technical advisor for HNTB Corporation in Kansas City, Mo.

Standard 8-ft-wide by 20-ft-long shipping containers were stacked on top of self-propelled modular transporters and secured by custom-fabricated container corner beams and ¼-in. chains to achieve the perfect height to erect the girders. Photo: Key Constructors.

CONCRETE BRIDGE PRESERVATION

CBP

Preserving Our Infrastructure by Using Modified Silica Gel

by Mario Baggio, Alchemco

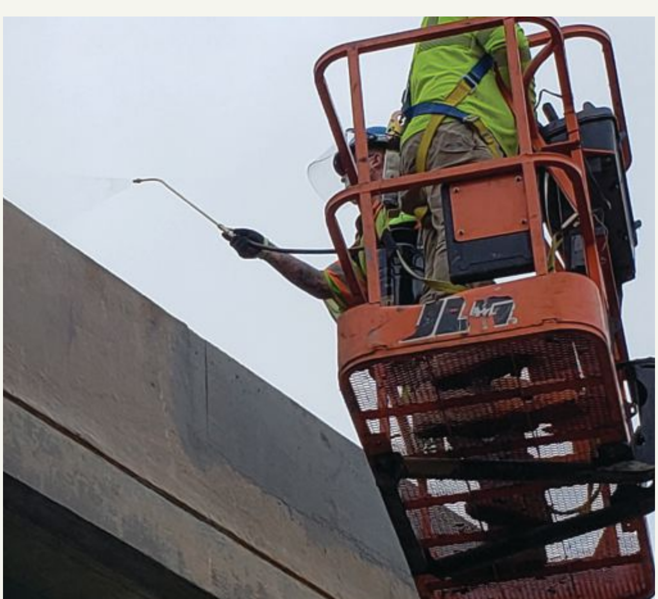
The bridge infrastructure in the United States is aging. Maintaining our bridges is crucial to our transportation system, and yet while department of transportation agencies around the country are focusing on bridge preservation and preventive maintenance, many of those same state agencies are faced with budget cuts year after year. According to a 2015 report by Purdue University for the Indiana Department of Transportation,[1] more than 50% of the national bridge inventory has exceeded a 50-year service life, and 25% of existing bridges are rated as structurally deficient or functionally obsolete. New bridge preservation technologies will help the United States and many other countries make their infrastructure last decades longer.

Key Factors in Bridge Preservation

Regularly preserving and maintaining bridges has been shown to be more effective than performing intensive and expensive repairs. When agencies are making choices on how best to spend their limited bridge maintenance and repair budgets, there are a few key things to think about.

In particular, a protection system for concrete surfaces of bridges should ideally fulfill several criteria. It should be durable and not rely solely on external protection, which can delaminate or wear away. A product that protects a bridge deck in summertime but gets scraped off by snowplows in winter or is worn off by year-round traffic is a poor choice for long-term protection. The system should also protect steel reinforcement from corrosion.

A protection system that is not porous will help prevent graffiti from adhering, but it should still be possible to paint over the system (for example, for striping). A system that seals cracks, thereby preventing premature deterioration of concrete, is advantageous. It is also important to get the bridge back in service quickly.



Spray application of modified silica gel on a bridge barrier for a Delaware Department of Transportation project. All photos: Alchemco.

Water is applied to activate modified silica gel that was previously applied on a bridge barrier for a Delaware Department of Transportation project.

A penetrating sealer and waterproofing product is a good choice to fulfill these criteria. Cracks need to be sealed against chloride ions to protect the steel reinforcement. But applying a product on the outside to seal the cracks may not be the best option, because an external protective surface can wear away and still leave the problem on the inside.

Bridge Preservation Using Silanes and Siloxanes

Silane- and siloxane-based sealers penetrate the concrete surface and chemically react to form a hydrophobic (water-repellent) barrier within the pores. The barrier, once formed, will last five to seven years. These sealers reduce concrete damage and deterioration caused by the absorption of surface water, such as cracking, spalling, pitting, mold and mildew, and efflorescence.

Silane-based products are increasingly being used for a variety of reasons. Silane molecules are slightly smaller than siloxane molecules and will penetrate more deeply, but the smaller molecule size also makes silane more volatile than siloxane (with a greater potential to evaporate after application).

Either silane or siloxane is appropriate for new bridges or reapplications on existing bridges. But, while they do create a hydrophobic surface to prevent water intrusion and damage over time, silane and siloxane do not seal cracks, which is the main concern for long-term durability.

Bridge Preservation Using Modified Silica Gel

Modified silica gel products are sprayable liquids that penetrate into the concrete using water as a transport mechanism. The products are sprayed on the surface of the structure and travel ½ to ¾ in. deep into the concrete by the process of diffusion. Properly prepared concrete surfaces that are clean, dry, dust free, and at least 28 days old are necessary to ensure success of the system.

When installed, these products form an impermeable and flexible waterproof structure inside the concrete. The gel interacts with calcium hydroxide and other by-products from the hydration process, which form as the concrete cures, to block capillaries, cracks, microfractures, and the like.

Modified silica gel can be used on new or existing concrete. In this application, the transport water is an ally, not an enemy, because the active ingredients of the gel use available water to migrate through the cracks and pores to penetrate deep into the concrete.

The organic ingredients in the modified silica gel, once they have been absorbed into the concrete and have been activated by water, give the concrete the ability to seal a surface crack whenever one may occur, which essentially gives the concrete "self-healing" properties. The active ingredients react with water to chemically change into a hydrophilic gel that seals cracks already in existence. The gel is absorbed into the concrete and remains present but dormant until it is reactivated by water. It subsequently undergoes the same chemical reaction again when future water penetrates the concrete and heals cracks as soon as they form. This attribute persists over the life of the concrete. Modified silica gel can heal potential future cracks that are up to 0.08 in. wide (about the width of a car key). Lab tests have shown that modified silica gel also acts as a densifier, increasing the hardness and compressive strength of the penetrated area of the concrete surface. When the gel is applied to a concrete deck at an early age, it can reduce the number of cracks and seal any future cracks that form.

Modified silica gel is being applied to seal individual cracks in a bridge deck for the Illinois Department of Transportation.

Penetrating sealers cannot be damaged or deteriorate like surface coatings. Moisture is not trapped in the concrete. The sealer allows moisture vapor outgassing while preventing ingress of water molecules and other deleterious materials. Modified silica gel is nontoxic, with no volatile organic compounds, and allows the concrete to be completely recycled after demolition. Also, it can be used over other integral waterproofing systems (like crystalline admixtures).

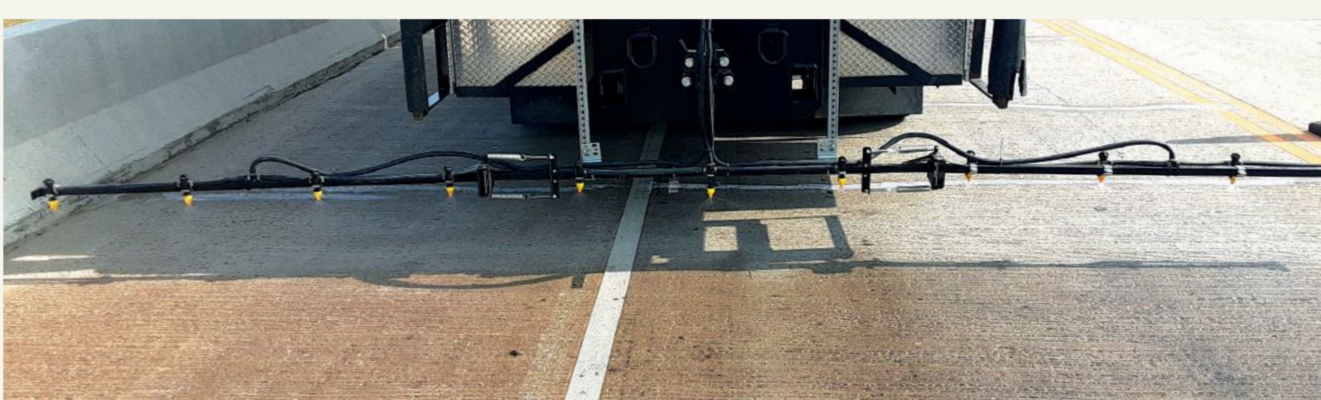
Conclusion

Protecting concrete bridge decks is an important part of bridge preservation. Modified silica gel is a durable waterproofing system that can extend the service life of our concrete infrastructure. Other systems, such as silanes and siloxanes, can and do protect against water, but they do not provide a long-term solution for the most common problem with concrete: cracking. Because of the unique crack self-sealing and waterproofing properties of silica gel, its use can reduce the direct cost for maintenance and repair.

Mario Baggio is the chief executive officer of Alchemco, a company that specializes in moisture and surface protection of concrete, in Henrico, Va.

Reference

1. Bowman, M. D., and L. M. Moran. 2015. *Bridge Preservation Treatments and Best Practices*. FHWA/IN/JTRP-2015/22. West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316007.



A spraying rig that can cover up to 100,000 ft^2 per hour applies modified silica gel to a bridge deck for the South Dakota Department of Transportation.

CONCRETE BRIDGE TECHNOLOGY

Detailing Segmental Concrete Box Girders for Constructability

by Jeremy Johannesen, McNary Bergeron & Associates

Bridge design and construction are an exercise in optimizing opposing forces. As part of this, structural detailing must balance design demands with practicality. The construction engineer's role, and specifically the detailing of integrated shop drawings, provides a unique perspective into the interface between design and construction. This experience allows us to explain why some things work "on paper" but prove to be problematic in the field. Constructability—how well things go together—is a subjective term, but there are some fundamental aspects to good detailing.

The foremost consideration should be tolerances. Just as design requires safety factors, construction also requires a margin for error. How great a margin depends on the nature of the details. Apart from the people who build them (who also require some tolerance), concrete segmental bridge construction has three key ingredients: concrete, post-tensioning, and reinforcement.

Concrete

When the design plans call for an 8-in.-thick slab, the end product is generally very close to that. Problems tend to occur when joining concrete elements from different forms. In segmental construction, wet joints are often used to connect precast concrete elements to cast-in-place (CIP) sections at substructure connections or where CIP construction is more practical (**Fig. 1**). From experience, we know that two elements can satisfy their own dimensional tolerances but not match each other. This can result in misaligned slabs and other features. There are two solutions for misaligned slabs. The first is to thicken the cross section on one side of the joint to ensure that the full design thickness is met across the joint. The other solution is to design a longer wet joint to smooth any kinks (**Fig. 2**).

Post-Tensioning

Construction specifications generally give post-tensioning (PT) ducts, anchors, and hardware the right of way when conflicts arise. In this hierarchy, PT can do no wrong unless it conflicts or does not align with itself. This can happen as in the previously mentioned case when joining tendons from two concrete elements cast in different forms are misaligned. Whenever possible, the best solution is to provide details with some free length of tendon duct to reduce or eliminate abrupt angle changes or kinks.

In the example shown in **Fig. 3**, precast concrete segments framing into a straddle beam were designed to sit high enough to allow the top-slab tendons to pass over the top of the beam. This avoided the need to precisely set ducts in the CIP straddle beam amid the heavy reinforcement at the top of the beam.

For tendons crossing through the straddle beam from the webs and bottom slab, other means were required to reckon with construction tolerances. In this case, blockouts were formed around the ducts in both the CIP straddle beam (**Fig. 4**) and in the adjoining face of the segment. The additional length of duct in the blockouts provided flexibility, allowing misalignments to be accommodated as smooth curves rather than sharp kinks.

A secondary consideration with PT is the actual size of the hardware. The corrugated plastic duct used in most systems has an outer diameter that is approximately 15% larger than the inside diameter. For example, a duct with a 4 in. inside diameter used for a 19-strand tendon actually has a 4.6 in. outer diameter. Knowing the real size of the hardware is key to making it fit and avoiding conflicts in the field.

Figure 1. At the St. Croix Crossing in Oak Park Heights, Minn., a cast-in-place pier cross beam interfaces with a precast concrete segmental box-girder superstructure. In some cases, both the cast-in-place element and the precast concrete segment can satisfy their own dimensional tolerances but not match each other. All Photos: McNary Bergeron & Associates.

Figure 2. Example of a short wet-joint closure where location variations in duct layout between cast-in-place and precast concrete elements have resulted in post-tensioning duct misalignments. The use of a wet-joint closure provides space to accommodate such duct alignment variations.

Reinforcement

There are numerous considerations for reinforcement tolerances. To begin, most reinforcing bars are approximately ¼ in. larger than their nominal diameter. While this added width sounds harmless, it can accumulate to make bad situations worse. It is always good practice to verify that the overall width of all crossing bars (and tendons) does not exceed the space available.

Figure 3. A precast concrete segment erected against a cast-in-place (CIP) straddle bent for the Hong Kong Mass Transit Railway's South Island Line. The precast concrete segments have been designed to sit high enough to allow top-slab tendons to pass over the CIP beam, avoiding the need to align these ducts between the CIP beam and precast segments. The deck above the top of the straddle beam is cast at the same time as the wet joint. Post-tensioning ducts near the top of the web (indicated with arrows) have been detailed slightly lower than other ducts in the top flange to accommodate reinforcing bar bend tolerances in the stirrups (see Fig. 5).

Figure 4. Formwork for the face of the CIP straddle beam where additional tolerance has been created by placing blockouts around post-tensioning ducts where they enter a wet joint (ducts will be installed in holes in blockout, indicated with arrows). The blockout increases the length of the ducts crossing the splice, adding flexibility to connect the ducts to the precast concrete segment.

Reinforcing bar fabrication also brings imperfections. Acceptance tolerances for bent bar dimensions are generally ±1 in. Tighter tolerances are only achieved by measuring each bar and rejecting nonconforming bars, which translates to added material and labor costs.

Where reinforcing bars are supported on chairs, the full length variation must be taken up at one end. In these instances, it makes sense to dimension bars slightly short and ensure that the details allow for the minus tolerance. An example for consideration is when PT is required near the top of a beam and "short" stirrups may conflict with the duct. In such cases, shifting the ducts down to provide a margin for tolerances avoids changes during construction (**Fig. 5**). For example, the ducts in the top slab shown in Fig. 3 have been lowered slightly near the web, compared to other ducts in the top flange, to allow for reinforcing bar tolerances in the stirrups.

In conjunction with length tolerances, reinforcing bar bends around the inside of reentrant corners should be avoided (**Fig. 6**). This detail is problematic primarily because it induces a "pop-out" force when the bar goes in tension. Even if restrained with ties, this detail is sensitive to reinforcing bar bend tolerances.

In addition to length tolerances, every reinforcing bar bend has acceptance tolerances for angular and out-of-plane deviations. This can be observed when reinforcing bars are being sorted for placement—bent bars often appear twisted and do not lay flat. Smaller-diameter bars can be tied into neat alignment during placement; however, fitting a twisted bar to other tightly spaced bars can require additional effort. For the record, sledgehammers should not be considered a standard reinforcing bar placing tool. Extensive use of "beaters" indicates a lack of consideration for tolerances or nonconforming reinforcement.

Figure 5. Partial view of box-girder web showing web bar tolerances. When post-tensioning is required near the top of a beam, "short" stirrups may conflict with the duct. Shifting the ducts down provides a margin for tolerances.

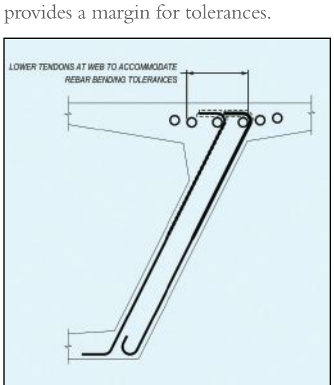
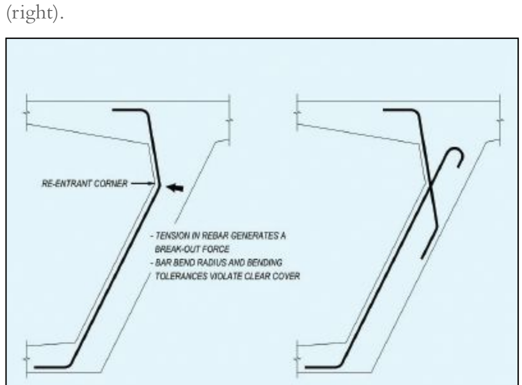


Figure 6. Partial view of box-girder web showing reentrant corner web bar details. Reinforcing bar bends around reentrant corners are problematic because they induce a "pop-out" force when the bar goes in tension (left). Reinforcement that crosses at the corner is a better detail (right).



Accurate placement becomes more important as the amount of reinforcing steel increases. Bar placing tolerance represents a two-way street; it allows bars to be shifted to accommodate the previously described issues or when misplaced as initially set, either of which can result in a domino effect of unanticipated changes. While this point leads to a separate discussion of layout, the remedy is the same: provide reasonable gaps between bar sets—the definition of "reasonable" is subjective, but a good rule of thumb is to provide approximately 2 in. of clear space between sets for every 10 in. of nominal reinforcing bar width.

Conclusion

Detailed design for segmental bridge construction can be tedious, and consideration of details adds one more check on top of many others. But the reality is that tolerances must eventually be dealt with, either on paper or in the field. For that reason, it is in everyone's interest to consider what happens if things are not executed perfectly and how to mitigate the consequences. Addressing these questions early avoids problems and helps put any project on the road to success.

This article focusing on tolerances is the first of two articles on constructability in segmental box-girder bridges. The next article will outline strategies to standardize and integrate details with the goal of making these bridges less complex.

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

A PROFESSOR'S PERSPECTIVE

The Role of Analytical Tools in Innovation

by Dr. John Stanton, University of Washington

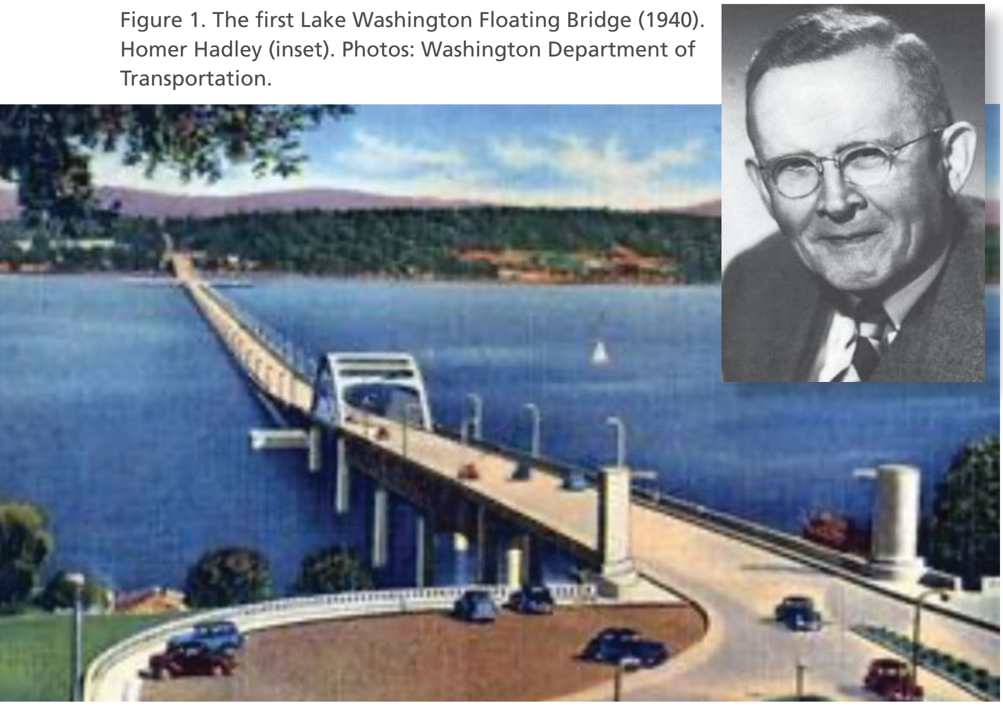
Computers and their software are both the boon and bane of our profession. The boon is easy to recognize: Computers save enormous amounts of time that were previously spent doing tedious, repetitive calculations. They also make possible much more sophisticated structural models, which are capable of predicting behavior more closely than could ever have been achieved with previous computational technologies, like hand calculators, slide rules, and pencils. (To those of you with youth on your side: google "slide rule.")

So, what is the bane? The problems probably lie not so much with the machines as with us. The machines do so much that we come to rely heavily on them, and it becomes harder to recognize the point at which we should start to question their electronic wisdom. We should also ask how we can best harness their powers for our benefit. These are the issues I would like to explore here, in the context of innovation.

Innovation is the engine of progress. And if we do not innovate and build that better mousetrap, someone else will, and we will find ourselves at a disadvantage. Furthermore, new challenges are constantly arising, and they call for appropriate, and often new, solutions. Bridge engineers carry an enormous responsibility for public safety and cannot afford to undertake risky innovations. That responsibility differentiates the profession from, say, builders of apps for tracking exercise regimens, but the pressure to innovate is there in both cases. Innovation in engineering takes a combination of a strong understanding of the underlying behavior, a thick skin (getting used to being called crazy), and the tools to develop the idea to fruition.

The first floating bridge across Lake Washington in Seattle, Wash., (**Fig. 1**), provides an example. Homer Hadley worked for the cement industry and saw that the lake was too deep and wide, and its bottom too muddy, to build a suspension bridge economically. So, he approached the state bridge engineer with the idea of using a series of hollow concrete pontoons to build a floating bridge. It would be anchored to the lake bottom with inclined cables. History does not relate the number of times that he was told he was crazy to think that concrete would float, but eventually, in 1940, the bridge was built, although it was named after the state bridge engineer, and not Hadley. It was followed over the course of time by three other such bridges in the region, using the same principles. The Interstate 90 (I-90) Lake Washington Floating Bridge sees relatively modest wave loading and was designed without computers. The Hood Canal replacement floating bridge, built in the early 1980s, also in Washington state, experiences more onerous loading; it crosses salt water and sees a 12 ft tidal range as well as dynamic loading from larger waves. Computing power provided much improved modeling capability and was clearly important for the design of this bridge.

Figure 1. The first Lake Washington Floating Bridge (1940). Homer Hadley (inset). Photos: Washington Department of Transportation.



More recently, the floating bridge provided the need for another innovation. Sound Transit planned to extend its light rail network from Seattle, over Lake Washington, to Bellevue. The obvious route was over the I-90 floating bridge. But the lake level rises and falls, controlled physically by the locks to Puget Sound, and administratively by the Army Corps of Engineers. Elevation changes require a transition span at each end to serve as a "gangplank" from "ship to shore," and the hinges at their ends undergo concentrated rotations as the water level rises and falls. The rotations are barely noticeable for rubber-tired vehicles, but they pose a real problem for fixed steel rails. Enter Andy Foan, who thought up a way of spreading the rotation over a length of rail great enough that it could be accommodated by elastic bending while at the same time vertically supporting the rails at the standard 30 in. tie spacing.[1] It is a clever three-dimensional (3-D) solution to a 2-D problem where no

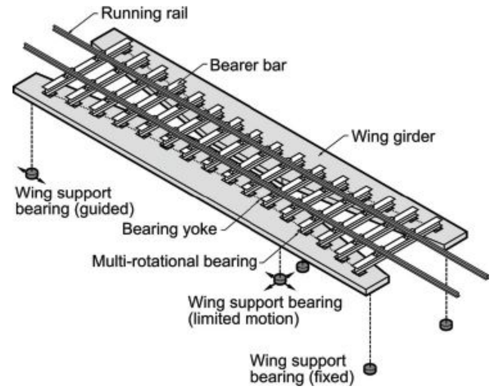


Figure 2. Curved-element-supported rail system at hinge in the existing Lake Washington Floating Bridge accommodates multidirectional movement for the new Sound Transit light rail extension. The concept was first modeled by Andy Foan using coffee stir sticks. Figure: Travis Thonstad.

adequate 2-D solutions could be found (**Fig. 2**). Foan claims to have dreamed up the idea when he was stirring his coffee at a coffee shop, and his first model was indeed made from coffee stir sticks. That was followed by a lot of head-scratching, sophisticated computer analysis, and proof-of-concept testing before the idea could be accepted and the prototype designed and then tested at full scale. It is, as yet, the only application of the idea worldwide. In this instance as in many others, the innovation was kick-started without computers. But, because of the geometric complexities, computing technology was almost essential to verify it and conduct detailed design.

How can we foster innovation? Measures should start in universities (or earlier), where "failure" costs nothing. We should provide students with opportunities to let their imaginations run free in developing concept designs for structures (such as bridges), and then apply basic tools of analysis to evaluate for themselves whether the design will work. It is humbling to prove that your own brilliant idea will not work, but the lessons learned through such trial and error stay with you for life, and they build the store of knowledge that is the basis for that elusive quality we call "judgment." This approach requires that the students have the tools to do the analysis. I would argue that, at this stage, simple tools are better than sophisticated software, because of the risks of using the latter inappropriately and coming to a wrong conclusion. The time for the advanced software comes later, during detailed design.

A second feature of innovation is a willingness to question conventional wisdom, and to reject it if reason finds it wanting. This is hard for both students and practitioners to do because much of conventional wisdom is embodied in codes and specifications. Students are bedazzled by today's codes (the American Concrete Institute's *Building Code Requirements for Structural Concrete* [ACI 318][2] has grown in length by a factor of approximately 8.6 since 1963, and the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[3] are much longer), and practitioners often find themselves bound by them. But questioning the code is the engineering equivalent of natural selection in biological systems, and it is essential for improvement. Of course, the right to question comes only with the obligation of listening to the answer.

An example is provided by the serendipitous birth of the use of unbonded post-tensioning for recentering of structures under seismic loading. A 10-story concrete frame building was constructed near Seattle in the early 1980s. The designer had provided the necessary reinforcing steel in the beams for the seismic and gravity forces, but they had added some unbonded post-tensioning to the beams, ostensibly for deflection control. For complicated reasons that are beyond the scope of this article, the owner had his own building condemned and then sued the builder and designer for code violations. The basis was that ACI 318 prohibited the use in seismic frames of steel with a yield strength greater than 78 ksi. A laboratory test of an exterior beam-column-slab joint was eventually arranged and was conducted at the University of Washington.[4] Despite the many inappropriate details of the test specimen, such as top beam bars hooked upward and in the front face of the column, rather than downward at the back face, the beam-column system performed remarkably well. It was clear to the team that the unbonded post-tensioning gave the system real potential, even though it clearly violated a well-meaning code provision. From that inauspicious start, the concept of deliberately using unbonded post-tensioning to recenter a seismic system was developed. It gained recognition in the Precast Seismic Structural Systems (PRESSS) program[5] and has been copied and adapted by the steel and timber industries for moment frames, shear walls, and braced frames. This innovation is now used in many countries susceptible to earthquakes (the United States, New Zealand, Japan, Italy, and various Central and South American countries). ACI 318 now recognizes and permits such systems. The moral of the story is that there is no formal route to innovation—sometimes, it is started by an accidental finding. Question conventional wisdom, even in codes.

The foregoing examples make the case for iconoclastic thinking and simple models of behavior to initiate innovation. If we all behaved like that all the time, the profession would be an unruly place. The initial, simple models should be thought through carefully, but frequently they alone are not enough. This is particularly true of statically indeterminate structures, in which the material behavior, including creep and cracking, plays a significant role. (Of the three pillars of structural mechanics—equilibrium, compatibility, and constitutive laws—constitutive laws are by far the most difficult). Large post-tensioned box-girder bridges, constructed using the balanced-cantilever method, provide a good illustration.

Podolny's comprehensive paper[6] describes many of the problems that can occur, most of which are associated with the changing distribution of stresses in the indeterminate structure. For example, Bazant and coauthors[7] discuss the Koror-Babeldaob Bridge in Palau, which collapsed after displaying large creep deflections.

In Seattle, the West Seattle Bridge, which was opened to traffic in 1984, was closed in March 2020 because ominous cracks had appeared in the webs and bottom flange (**Fig. 3**). The cause has now been traced back, with a high level of certainty, to the fact that creep strains and deflections caused the inflection points in the main span to migrate outward toward the main piers, thereby increasing the length of the positive moment region. That region eventually grew to encompass the anchor locations for the positive moment tendons, and the stress concentrations there initiated the cracking. This behavior could be identified in principle with a pencil and paper, but demonstrating it beyond a reasonable doubt was possible only with

Figure 3. Epoxy-injected cracks in the West Seattle Bridge (2020). Photo: John Stanton.

a sophisticated finite element model that included time-dependent constitutive behavior. Such tools are indispensable for complex problems of this sort.

We need both sophisticated analytical tools and simple tools, and we need them for different purposes. But let us not become so enraptured by the sophisticated ones that we lose the mental models of structural behavior that are one of the main engines of innovation.

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EDITOR'S NOTE

The West Seattle Bridge was one of the early segmental concrete box-girder bridges constructed in the United States. When the structure was designed, it was still not well understood how such bridges should be designed and detailed to deal with long-term effects. Unfortunately, the design and details for the West Seattle Bridge did not allow the structure to accommodate an inexact prediction of long-term behavior. Designers have since developed solutions for those issues that are now standard practice. This is a further demonstration of the need to understand underlying behavior and the limitations or variabilities of our numerical models.

Designing for Construction Loads on Concrete Bridges

by John W. Jordan, Kiewit Engineering Group Inc.

Design engineers use risk management to control or limit design-related uncertainty for the safety of construction personnel and the traveling public. In construction, there is a great deal of uncertainty and risk that must be managed effectively; for example, in addition to safety concerns, there are risks related to cost, quality, schedule, construction means and methods, aesthetics, and environmental impact constraints that may affect design choices. These risks may be considered in one of three ways: ignore the risk, avoid the risk, or design for the risk. Designing for risk requires a thorough understanding of the structure and the variety and uncertainty of the forces that may affect it.

Numerous bridge construction accidents have been attributed to a failure to appropriately consider construction means and methods—the effects of construction loads in particular. Unfortunately, construction loads have long been an underemphasized topic in many specifications and design manuals. For example, the August 1, 2007, collapse of the Interstate 35W bridge in Minneapolis, Minn., was attributed in part to concentrated construction loads on the bridge on the day of the collapse. Following its investigation, one recommendation from the National Transportation Safety Board to the Federal Highway Administration was to "develop specifications and guidelines for use by bridge owners to ensure that construction loads and stockpiled raw materials placed on a structure during construction or maintenance projects do not overload the bridge's structural members or their connections."[1]

The American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[2] is primarily a design-oriented specification, with limited direction or guidance with respect to construction loads. Article 2.5.3 of the AASHTO LRFD specifications, ninth edition, includes the following:

> *Bridges should be designed in a manner such that fabrication and erection can be performed without undue difficulty or distress and that locked-in construction force effects are within tolerable limits.*
>
> *When the designer has assumed a particular sequence of construction in order to induce certain stresses under dead load, that sequence shall be defined in the contract documents.*
>
> *Where the bridge is of unusual complexity, such that it would be unreasonable to expect an experienced contractor to predict and estimate a suitable method of construction while bidding the project, at least one feasible construction method shall be indicated in the contract documents.*

Construction of new bridges, or rehabilitation or widening of existing bridges, often requires operating heavy equipment on the bridge. As work areas become congested and adjacent construction staging areas are limited, the need to place loads on bridges increases. Construction loads, whether from material stockpiles or equipment, can be of substantial magnitude and produce load effects that differ significantly from those for which a bridge was designed. Construction loads are often of short duration and highly variable. Loads may be concentrated resulting in load effects that may be greater than those of the design vehicles. The effects of construction loads—for example, residual forces and deformations from removal of temporary loads or supports—may remain a consideration after construction is complete. Also, elements and connections of the completed structure that ultimately provide strength, stiffness, stability, or continuity may not be present during certain phases of construction. For these reasons, it is important to assess the effects of construction loads during design.

An overhead gantry is used for the construction of the U.S. 17 bypass near Washington, N.C. The structure must be analyzed for the loads from specialized equipment. Photo: Flatiron Construction Co.

It is recommended that design engineers consult with contractors experienced in the erection procedure that is being recommended to obtain the most accurate construction loading information. Construction loads and conditions frequently impact section dimensions and reinforcement, prestressing, or post-tensioning requirements in segmentally constructed bridges. Bridges should be checked for construction loads to ensure that structural damage will not occur during the construction process, and that the construction means and methods have no adverse impact on the service state or service life of the completed structure.

Safe construction of a bridge requires proper coordination, delegation, and exchange of information among the designer, contractor, and owner. Many construction accidents are caused simply due to an improper erection sequence or process.

The design engineer is responsible for designing the bridge per the AASHTO LRFD specifications and the state- or agency-specific policies documented in their design manual, guides, and standard plans. Subsequently, a contractor with sufficient expertise and experience constructs the bridge per the design documents and project specifications. The contractor selects qualified suppliers to provide materials and structural elements for the bridge to ensure constructability, safety, and durability. Responsibilities for the design of temporary structures and temporary supports, for the evaluation or design of partially completed structures for temporary use or construction loads, and for supervision of site activities to control loads on structures are typically delegated to the contractor or the contractor's construction engineer.

Girder erection on Cow Key Channel Bridge in the Florida Keys. When adjacent construction staging areas are limited, erection equipment may need to be placed on an unfinished structure. The structure must be evaluated for these erection loads. Photo: Kiewit Construction Co.

It is, however, the responsibility of the design engineer to include in the contract documents critical design assumptions that can impact the integrity of the structure. The assumed method of construction—including any temporary supports that are required before the structure, or component thereof, can support itself and subsequently applied loads—should also be shown in the contract documents. The maximum construction loads and their locations for which the structure has been evaluated should be quantified. Simple designs can avoid mistakes that arise due to lack of expertise; therefore, wherever possible, simple designs are advisable. Design drawings should be unambiguous, complete, and logical for those involved in the actual construction.

Construction loading analysis should consider, but not necessarily be limited to, the following:

- Erection loads
  - Construction live load: an allowance for miscellaneous items of materials, machinery, and other equipment, apart from specialized erection equipment.
  - Specialized construction equipment load: the maximum loads and load effects from segment or material delivery trucks, or both, and any special equipment, including a crane, form traveler, launching gantry, beam and winch, truss, or similar auxiliary structure during erection.
  - The distribution and application of the individual erection loads appropriate to a construction phase should be selected to produce the most adverse effects.
  - Realistic (not overly conservative) self-weights to ensure the final deck geometry will be correct. For example, an exaggerated concrete density of 165 lb/ft^3 may be specified by the owner for post-tensioned concrete in an attempt to be conservative, but its use may lead to unrealistic geometry and large (unconservative) locked-in permanent load effects and creep redistribution.
- Temporary supports and restraints
  - The stage of construction during which the temporary supports are removed.
  - Residual forces and deformations and/or strain-induced effects from removal of temporary loads and supports.
- Stability of partially erected structures
- Deck placement sequence, if applicable
- Girder stability during lifting and erection and while the element is braced before the deck is placed
- Structural condition of the existing structure to support demolition loading and/or construction loads
  - If the design requires strengthening of an existing structure and/or

Demolition of the Coastal Highway Bridge over the Lewes-Rehoboth Canal near Dewey Beach, Del. An existing structure must be analyzed for the loads from demolition equipment and for overall stability. Photo: Kiewit Construction Co.

- temporary bracing or support during erection or demolition by the selected method, the need thereof should be indicated in the contract documents.
- Environmental and hydraulic conditions that may affect the construction of the bridge

A time-dependent and multistage analysis must be used for any bridge where the structural statical scheme undergoes changes before reaching construction completion (as in segmental construction). Such analysis should also be performed where there are changes in the cross section of superstructure members through composite action and prestressing is applied to the noncomposite and composite cross sections (as in spliced girder construction).

There have been several initiatives that have advanced the state of practice related to the design and construction of temporary works used in bridge construction. For example, the AASHTO *Guide Design Specifications for Bridge Temporary Works*,[3] the American Society of Civil Engineers/Structural Engineering Institute's *Design Loads on Structures during Construction* (ASCE/SEI 37),[4] and the AASHTO *Construction Handbook for Bridge Temporary Works*[5] can all serve as useful references for construction loads.

Bridges are unique structures, so it is advisable to partner with designers and contractors experienced in bridge erection. Always design to code and leverage the latest proven design and construction techniques. If during construction, there is ever a concern about the application or effect of a construction load, stop work until the concerns are addressed.

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Eliminating Bridge Joints with Link Slabs

by Raj Ailaney, Federal Highway Administration

A functional expansion joint is paramount to the longevity of a bridge. When adequately designed, correctly installed, and maintained, it allows the bridge to expand and contract as temperature changes, accommodates rotation of the beam ends, and contains surface runoff. However, bridge owners have struggled in the past to maintain expansion joints. Joint failure can cause leakage that leads to premature deterioration and failure of beam ends, bearings, and underlying substructure elements (**Fig. 1**, **2**).

The Federal Highway Administration (FHWA) published the downloadable *Bridge Preservation Guide*[1] in the spring of 2018. This guide defines bridge preservation terms and identifies commonly practiced bridge preservation activities. It provides examples of cyclical and condition-based maintenance activities that extend the service life of a bridge and its components. Bridge owners may use these activities to keep their bridge inventory in a state of good repair, and these activities are eligible for federal funds. Joint elimination is one of the eligible condition-based activities.

Developing strategies to eliminate bridge joints is not new: integral abutments were developed in the 1970s specifically to eliminate joints at the bridge ends.[2] Historically, for existing structures, a strategy to eliminate an existing joint has been to eliminate the joint and make the superstructure continuous. However, this method tends to be challenging for simply supported spans, as the continuous superstructure needs to handle the negative moment at the pier and requires strengthening both the girders and deck.

To mitigate leaking joints and to avoid strengthening the superstructure, some bridge owners have eliminated existing joints by replacing them with link slabs; a few owners are also conducting studies on material types, design, and impacts of link slabs on the overall behavior of the structure. Currently, the common understanding is that, although fine cracks may develop in a link slab installed to eliminate a joint, the presence of fine cracks is preferable to a deck with a leaking joint.

A link slab is constructed between two noncontinuous superstructure elements and is designed to support traffic wheel loads and the bending moment due to girder rotations. There are two types of link slabs: full depth (**Fig. 3**) and partial depth (**Fig. 4**). The link slabs are not intended to transmit live-load effects from one span to another, which would create girder continuity. Because span movement is restricted, a global analysis of the entire bridge must be conducted; this analysis must take into consideration substructure flexibility and bearing types that allow proper load distribution. Link slabs are not a panacea, but a tool to prevent surface runoff laden with harmful chemicals from attacking bridge beam ends, bearings, and substructures.

Recently, FHWA published *A Case Study: Eliminating Bridge Joints with Link Slabs—An Overview of State Practices.*[3] This case study presents an overview of the use of link slabs by four state agencies. The four agencies represented are the Virginia Department of Transportation (DOT), because it has installed more link slabs than any other owner in the country; the Massachusetts DOT, because it has used link slabs for accelerated bridge construction; New York State DOT (NYSDOT), because it has recently developed standard details and example calculations; and the Maryland Transportation Authority, because it has very recent research regarding

Figure 1. Leakage from failed or deteriorated bridge deck expansion joints can cause deterioration of beam ends, bearings, and substructure elements. All Photos and Figures: Federal Highway Administration.

Figure 2. Chemical-laden surface runoff can accelerate substructure deterioration beneath an expansion joint.

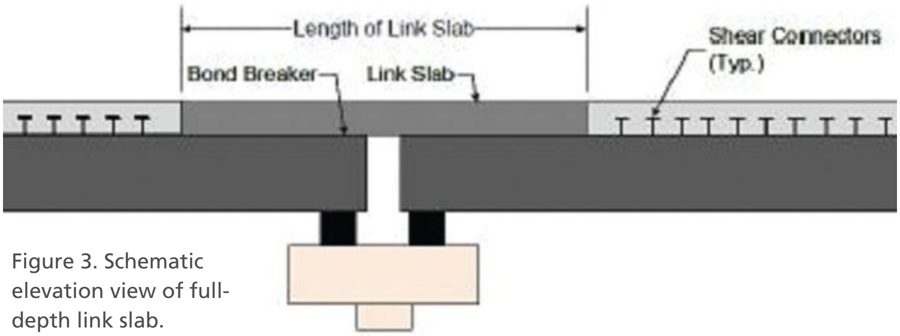

Figure 3. Schematic elevation view of full-depth link slab.

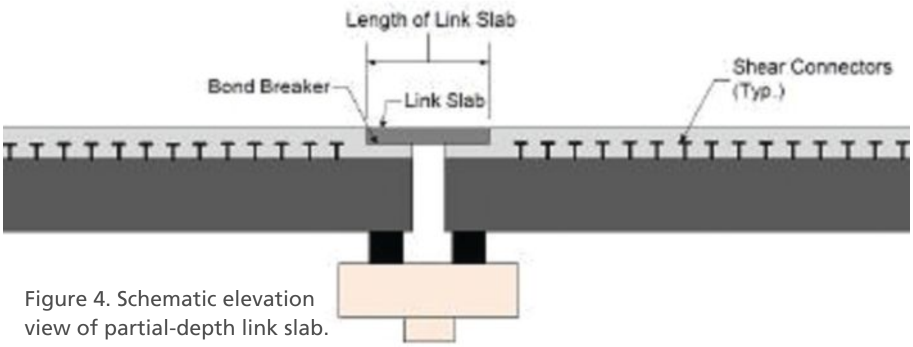

Figure 4. Schematic elevation view of partial-depth link slab.

link slabs. The case study presents the agencies' design approaches to evaluating the impact of installing a link slab on existing bearing types and mitigating concrete cracking, as well as design methodologies and materials used.

As one example, the NYSDOT uses the strain compatibility design method to evaluate the cracking potential of link slab concrete. Their material of choice is ultra-high-performance concrete (UHPC) due to its high tensile strength, high compressive strength, strong bonding to adjacent deck concrete, and low permeability. UHPC is a fiber-reinforced, cementitious composite material with mechanical and durability properties that far exceed those of conventional concrete materials (UHPC has been the topic of several recent articles in *ASPIRE*®—a general introduction appeared in the Spring 2017 issue).

NYSDOT designs link slabs for a maximum concrete strain of 0.0035 in tension and a maximum compressive stress of 14 ksi. The ability of UHPC to develop ultimate tensile strains up to 0.007 by development of microcracks allows the link slab to accommodate girder end rotations. A maximum design strain of 0.0035 (50% of the ultimate value) at the extreme tensile fiber is chosen to control crack width. Limiting the tensile strain increases the service life of the link slab by preventing cracking that would allow penetration of moisture and chemical-laden surface runoff.

The case study provides an example that illustrates the difference in bridge mechanics before and after installation of a partial-depth link slab. The initial condition (**Fig. 5**) has a joint at the simply supported ends of two adjacent spans at a bridge pier with one "fixed" bearing, allowing rotation but not translation, and one "expansion" bearing, allowing both translation and rotation. After installation of the partial-depth link slab and replacement of the existing bearings with elastomeric bearings (**Fig. 6**), the bearings are no longer required to rotate; instead, they only translate. The beam end rotation is accommodated by the link slab, which is designed to resist the flexure due to live-load girder end rotations. The use of a bond breaker between the link slab and the top of the girder prevents any continuity between spans. Reinforcement in the link slab is typically spliced to existing deck reinforcement. Bridge mechanics will differ if both the bearings are "fixed" or "expansion," which is why a full analysis of forces is warranted.

Through the Every Day Counts innovation initiative, FHWA will be promoting the use of UHPC in the preservation and repair of bridges by encouraging its use in link slabs, beam end repairs, and deck overlays. The implementation team will publish design guidance documents that describe UHPC, outline bridge preservation and repair applications, and include specific design and construction recommendations for link slabs, beam end repairs, and bridge deck overlays. Additional information on the use of UHPC for bridge preservation and repair can be found at https://www.fhwa.dot.gov/innovation/everydaycounts/edc_6/uhpc_bridge_preservation.cfm.

Joint elimination, where feasible by design and appropriate for structure behavior, is a condition-based preservation activity, and is eligible for federal funding. State DOTs, local agencies, and other bridge owners are facing significant challenges in addressing the needs of our aging infrastructure. Due to age, the number of bridges moving from good to fair condition is on the rise. The replacement of deck joints with link slabs as a bridge preservation activity is one of the few ways we can slow this trend and extend our bridges' service lives.

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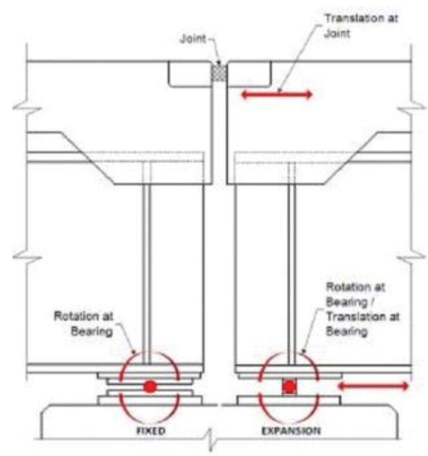

Figure 5. Typical deck joint at pier with movements indicated at deck and bearings.

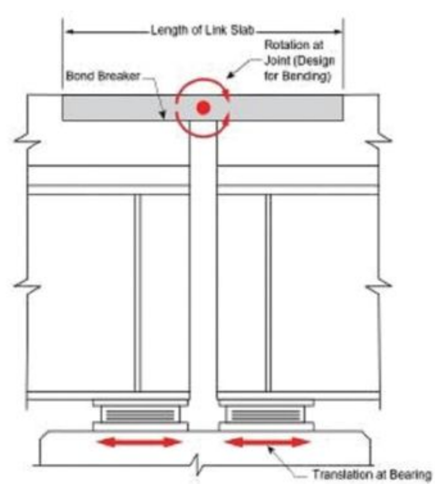

Figure 6. Typical partial-depth link slab at pier accommodating translation and rotation at deck and bearings.

CONCRETE CONNECTIONS

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

IN THIS ISSUE

https://www.hdrinc.com/portfolio/i-91-rockingham-bridges
The Interstate 91 (I-91) Rockingham Bridge, Vermont's longest precast concrete spliced-girder bridge, received a PCI Design Award and is the subject of the Project article on page 28. This website has remarkable construction photos of the bridge.

https://outside.vermont.gov/agency/VTRANS/external/Projects/Structures/Forms/AllItems.aspx?RootFolder=%2fagency%2fvtrans%2fexternal%2fProjects%2fStructures%2f12a130&FolderCTID=0x01200074B2F1F49FDD30448D18FC55BFA5E40000A-FA5164EB50FC64DBB5A49CE09B9CFEB
Documents such as a project fact sheet and the "2014 Rehabilitation Study Report" for the I-91 Rockingham Bridge project (page 28) can be downloaded from the Vermont Agency of Transportation website via this link.

https://www.jpcarrara.com/projects/rockingham-i-91-bridge
The long, haunched precast concrete girder segments for the I-91 Rockingham Bridge (page 28) were challenging to produce, transport, and erect. The largest girder was 96 ft long, weighed 187,000 lb, and required a truck with steerable trailer to transport. This is a link to a photo gallery of the production and erection of the girders on the precaster's website.

https://www.pci.org/PCI_Docs/Publications/PCI%20Journal/2021/January-February/Project_Spotlight_JF21.pdf
This is a link to a Project Spotlight article on the I-91 Rockingham Bridge (page 28) in the January–February 2021 issue of *PCI Journal*.

https://asbi-assoc.org/index.cfm/events/MonthlyWebinars
This is a link to the American Segmental Bridge Institute (ASBI) webinar page, which provides access to recordings of previous webinars, including the "JFK Causeway" webinar offered on April 28, 2021. The condition evaluation of the JFK Causeway Bridge, the first precast concrete post-tensioned segmental bridge built in the United States, is featured in the Project article on page 20.

http://www.trb.org/Publications/Blurbs/181972.aspx
The Project article on page 20 presents some of the findings of the recent condition evaluation of the JFK Causeway bridge. The recently published *National Cooperative Highway Research Program Synthesis 562: Repair and Maintenance of Post-Tensioned Concrete Bridges* includes a literature review, the results of a survey distributed to 50 state departments of transportation, current practices used by bridge owners to repair and maintain post-tensioned bridges, and lessons learned. The report can be downloaded from this link.

https://www.fhwa.dot.gov/bridge/preservation/docs/hif20062.pdf

The Federal Highway Administration (FHWA) article on page 46 discusses replacing expansion joints with link slabs. The article presents examples from the FHWA publication *A Case Study: Eliminating Bridge Joints with Link Slabs—An Overview of State Practices* (FHWA-HIF-20-062), which can be downloaded from this link.

https://abc-utc.fiu.edu/mc-events/lake-pontchartrain-causeway-bridge-safety-bay-construction-past-present
This is a link to an archived webinar produced by the Accelerated Bridge Construction Center at Florida International University on the Lake Pontchartrain Causeway Bridge safety bays project that is discussed in the Focus article on page 6 featuring the contractor Boh Bros.

https://www.soundtransit.org/blog/platform/crossing-lake-washington
The Professor's Perspective on page 40 uses the original construction and recent renovation of the floating bridge across Lake Washington as an example of an innovative solution. This is a link to a website that has a video with renderings of the technology to allow translation in six directions and clips of the full-scale testing for the new extension of the light rail transit system in the Seattle, Wash., region.

https://vtrans.vermont.gov/projects/middlebury
This is a link to the official website for the Middlebury, Vt., bridge and rail project that is the subject of the Project article on page 24. Stakeholder involvement was key to success of the project, in which closure of downtown Middlebury and the railroad was limited to a 10-week period. The website presents photos, frequently asked questions, project updates, documents, and a video of tunnel opening-day activities.

https://www.asbi-assoc.org/index.cfm/resources/videos
Segmental bridges are the topic of both the Concrete Bridge Technology article on page 38 and the Project article on page 20. This page of the ASBI website has links to informative videos on various aspects of segmental bridge construction.

https://ctr.utexas.edu/wp-content/uploads/pubs/0_5253_1.pdf
The LRFD article on page 49 discusses crack-control reinforcement and its implications. The article is based on a published research study, "Strength and Serviceability Design of Reinforced Concrete Deep Beams," which can be downloaded from this link.

OTHER INFORMATION

https://www.asbi-assoc.org/index.cfm/publications/segments
The Spring 2021 issue of the ASBI newsletter *Segments* is now available via this link.

Crack-Control Reinforcement: Strength and Serviceability Implications

by Dr. Oguzhan Bayrak, University of Texas at Austin

This article discusses the role of crack-control reinforcement, modeling of that reinforcement, both implicitly and explicitly, and background information on the crack-control reinforcement requirements of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[1]

Behavioral Difference between B-Regions and D-Regions

The behavioral difference between B-regions (beam or Bernoulli regions) and D-regions (disturbed or discontinuity regions) as defined in the AASHTO LRFD specifications can be understood by looking at the behavior of a typical beam.[2] The shear span *a* of a beam is the distance between the applied load and the reaction; the depth *d* is the effective depth of the member, or the distance from the extreme compression fiber to the centroid of the tension steel. Article 5.8.2.1 of the AASHTO LRFD specifications recommends that strut-and-tie modeling (STM) should be considered for members with $a/d < 2$ (that is, a low shear span-to-depth ratio). **Figure 1** shows results of a beam test that was conducted to compare the behavior observed in a short shear span ($a/d = 1.2$ on the left-hand side of the beam) and a long shear span ($a/d = 2.5$) on the right-hand side of the beam). At low loads ($P = 300$ kip), the strains measured in the lowermost layer of flexural tension reinforcement follow a strain pattern that closely mimics the moment diagram for this beam under a single concentrated applied load *P*. The strain profiles along the beam shown in Fig. 1 indicate that, with increasing loads and after substantial cracking of the beam (which occurred at a load of about 1000 kip), the behavior in the short shear span is quite different from that of the longer shear span. When the applied load exceeds 1500 kip, the strain in the flexural tension reinforcement is nearly uniform for the span with $a/d = 1.2$. This strain profile signals the formation of a direct strut associated with a truss-like behavior that has a constant tie force along the shear span. In direct contrast to the observed behavior in the short shear span, the right-hand side of the beam ($a/d = 2.5$) more closely follows Bernoulli-type behavior, in which plane sections remain plane and the strain response can be reasonably predicted using the moment diagram for this beam. Birrcher et al.[2] concluded that at ultimate load for long shear spans considered in their study (with $a/d = 2.5$), nearly two-thirds of the applied load was transferred into the support by internal shears and moments (Bernoulli beam response) and a third of the load was transferred directly into the support by a strut. In recognition of this behavior, the AASHTO LRFD specifications recommend differentiating B-regions from D-regions and using strut-and-tie modeling (STM) provisions to design the D-regions.

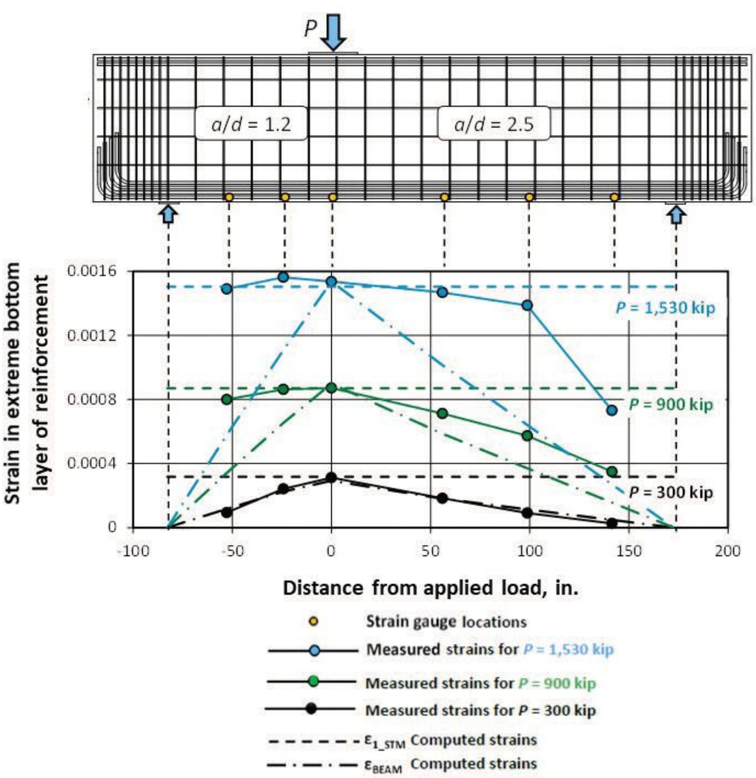

Figure 1. Test results for a specimen with short and long shear span–to–depth (*a*/*d*) ratios demonstrate the performance differences between B- and D-regions. Note: Strain gauge locations are shown in top figure. Solid lines with dots indicate measured strain response. *a* = the distance between the applied load and the reaction; *d* = the effective depth of the member; *P* = applied load; ε_{1_STM} = calculated strain using strut-and-tie model; ε_{BEAM} = calculated strain using beam model. Figure: Dr. Oguzhan Bayrak, adapted from Fig. 5.42 in Birrcher et al.[2]

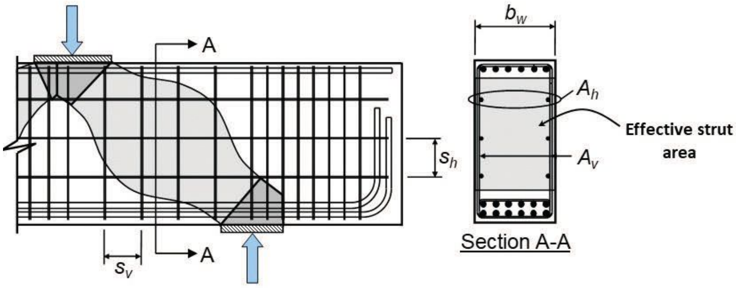

Figure 2. Compression spread and distribution of crack-control reinforcement in a diagonal strut. Note: A_h = total area of horizontal crack-control reinforcement within spacing s_h; A_v = total area of vertical crack-control reinforcement within spacing s_v; b_w = web width; s_h = spacing of horizontal crack-control reinforcement; sv = spacing of vertical crack control reinforcement. Figure: Dr. Oguzhan Bayrak, adapted from Fig. 3.8 in Birrcher et al.[2]

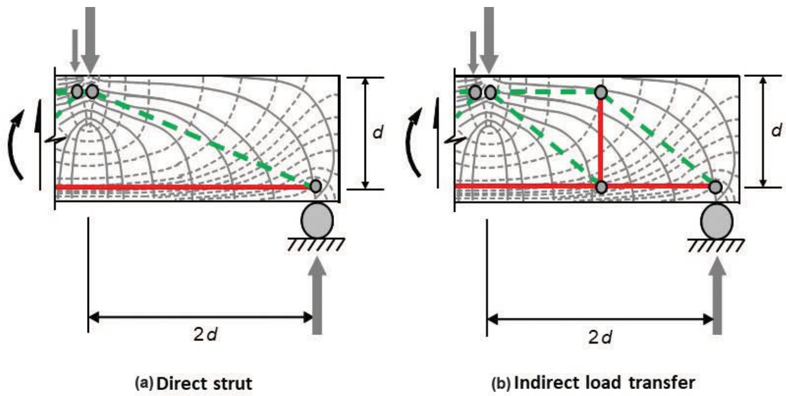

Figure 3. Comparison of models showing transfer of applied load to support by (a) direct strut and (b) indirect load transfer with a vertical tie. Figure: Dr. Oguzhan Bayrak, adapted from Fig. 2.5 in Birrcher et al.[2]

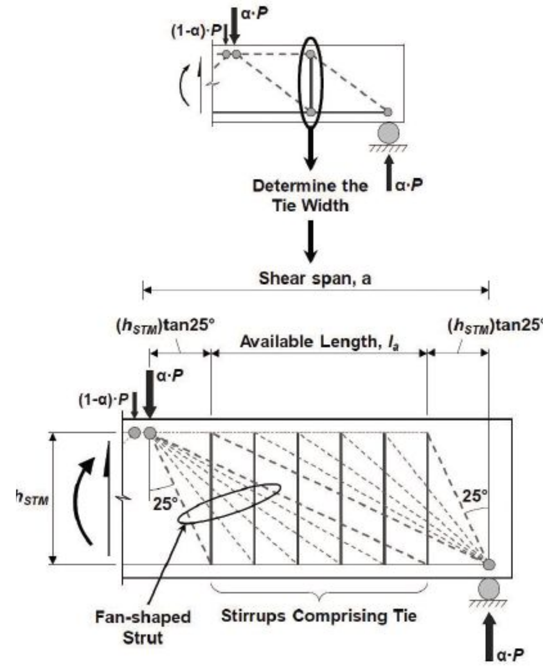

Figure 4. Example indicating available length in the shear span in which stirrups contribute to capacity of vertical tie. Figure: Adapted from Fig. C5.8.2.2-2 of the AASHTO LRFD specifications.[1]

Crack-Control Reinforcement

Although crack control reinforcement requirements vary for B-regions and D-regions, all elements (regardless of the region) designed using the STM design provisions must contain the appropriate amount of crack-control reinforcement specified in Article 5.8.2.6 of the AASHTO LRFD specifications, which requires the use of a minimum quantity of crack-control reinforcement. More specifically, Article 5.8.2.6 requires 0.3% reinforcement, defined as 0.003 times the effective area of the strut, which is provided in two orthogonal directions (horizontal and vertical in **Fig. 2**) as crack-control reinforcement. This reinforcement has two purposes related to strength and serviceability. Regarding strength, a grid of reinforcement is necessary to handle the transverse tension that results from the spread of compression in the diagonal strut (Fig. 2). Although the actual quantity of reinforcement needed to satisfy equilibrium of forces upon cracking of concrete is a function of material and geometric properties of the member, 0.3% reinforcement is typically sufficient to cover all cases encountered in bridge elements designed using STM. Regarding serviceability, Birrcher and colleagues[2] proved that use of reinforcement quantities that are less than 0.3% do not provide sufficient crack control. For example, in cases where 0.2% reinforcement was used as crack-control reinforcement, the width of the diagonal cracks exceeded 0.016 in. when they first formed and crack width increased with additional loading.

To model the spread of compression in a diagonal strut (Fig. 2), let us consider the direct and indirect load transfer mechanisms shown in **Fig. 3**. This figure shows that the direct load transfer mechanism (that is, a direct strut that forms between the load point and the near support) does not explicitly require the use of stirrups (Fig. 3a). However, the use of 0.3% reinforcement in each direction (not shown in the figure), in accordance with Article 5.8.2.6, accomplishes the goal of providing stirrups that act as shear reinforcement. Alternatively, if a two-panel truss is used (Fig. 3b), the vertical tie reinforcement can be explicitly evaluated and provided in the member. When using this approach, the available length, l_a, as defined in the right part of **Fig. 4**, should be used to identify those stirrups that will contribute to the capacity of the vertical tie. In other words, the tension resulting from the spread of compression in a strut can be explicitly modeled by using a vertical tie between the load and the support (Fig. 3b). Therefore, if a designer chooses to use the indirect load transfer model shown in Fig. 3b, the vertical reinforcement (stirrups) will partially or fully satisfy the crack-control requirements of Article 5.8.2.6 in the vertical direction. In contrast, the primary flexural reinforcement (top or bottom) shown outside of the effective strut area in Fig. 2 cannot be used to satisfy the crack-control reinforcement requirement in the horizontal direction because it does not contribute to controlling the width of cracks that may form due to the spread of compression in a strut.

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2. Birrcher, D., R. Tuchscherer, M. Huizinga, O. Bayrak, S. Wood, and J. Jirsa. 2009. "Strength and Serviceability Design of Reinforced Concrete Deep Beams." Technical Report 0-5253-1. Austin: Center for Transportation Research, University of Texas at Austin.

Ethics and Culture: You Can't Ride a Bike Without Wheels

by Dr. Anna B. Pridmore, Structural Technologies

Within our practice of the profession of engineering there are many intersections between ethics and culture. Whether personal, within the organizations we work and volunteer for, or as part of the project teams we are assigned to or lead, culture plays a pivotal role in the application of our code of ethics.

While working on the new American Society of Civil Engineers (ASCE) Code of Ethics over the past two years, I spent a lot of time considering the importance of ethics as we carry out the business of designing and engineering bridges and the built environment. In 2018, Robin Kemper, 2019 ASCE president and the person responsible for the vision to address the Code of Ethics, provided the following guidance to our task committee: "Approach the task as if drafting an ASCE Code of Ethics for the first time. Identify moral concepts that should be captured in a civil engineer's professional behavior. Document those moral concepts with concise, readable, and modern language."

The task committee included a dedicated group, with whom I was honored to serve: Brock Barry (chair), Stephanie Slocum, Lawrence Chiarelli, Monte Phillips, Mario Ricozzi, Peter Terry, Taylor Boileau, Tara Hoke (ASCE's general counsel and task committee representative), and myself.

One of the most important advancements in ASCE's new Code of Ethics was a shift to a stakeholder model to better articulate the responsibility engineers have to each stakeholder group (**Fig. 1**).[1] The ASCE Code of Ethics also establishes a hierarchy, as demonstrated in the numbered order of stakeholder groups (1 to 5), and leaves no question for ASCE members that our duty to society is the highest level: "first and foremost, protect the health, safety, and welfare of the public."[2] These words—health, safety, welfare of the public—appear in some form at or near the top of nearly every engineering discipline's code of ethics.

A code of ethics, or even the state laws pertaining to professional ethics, do not by themselves create an environment where "protecting the health, safety, and welfare of the public" is made the highest priority. The words within any code are by themselves static and lifeless without an engineer acting.

The difference between catastrophe and a near miss is whether the warning signs are heeded or ignored.

There are likely thousands of tragedies being averted through the daily actions of engineers who are consciously or subconsciously applying their code of ethics. One notable positive example took place in 1978 in New York City.[3]

Diane Hartley, an engineering student at the time, placed a call to the designers of the new 59-story Citicorp Center in New York City (**Fig. 2**). Hartley brought to the designer's attention that the building as constructed had a design error that made it susceptible to collapse under heavy wind loads. This single phone call started a chain reaction of events that potentially saved the building from collapse. Hartley's action, followed by the engineer of record taking immediate steps to retrofit the building, initiated a series of events that embody the prevalent "protecting the health, safety, and welfare of the public" foundation within engineering codes of ethics. What is it about Hartley's environment that empowered her to make that call? One word: culture.

As mentioned, Hartley was a student when she started the wheels in motion to correct the structural errors of the Citicorp building. A natural aspect of the academic culture is a willingness to be inquisitive and to ask questions. This led to the phone call and the steps that followed, all down a critical path that protected the health, safety, and

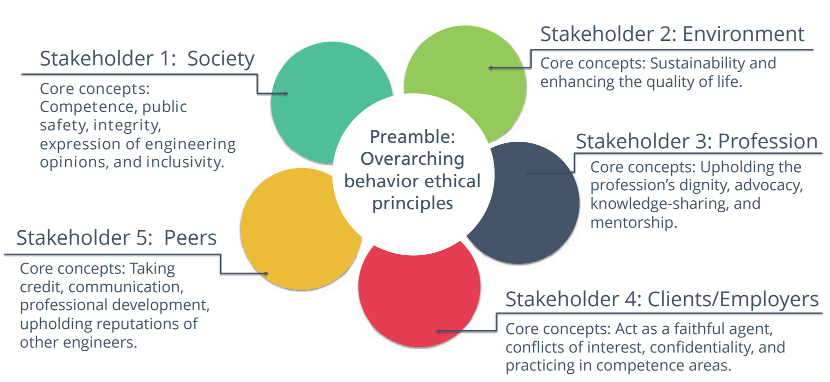

Figure 1. The stakeholder model forms the foundation of the new ASCE Code of Ethics. Figure: Stephanie Slocum on behalf of the ASCE Task Committee on Code of Ethics.

Figure 2. A single phone call started a chain of events that potentially saved the Citicorp Center in New York City from collapse. A culture of empowerment can bring the code of ethics to life and protect the health, safety, and welfare of the public. Photo: Structural Technologies.

welfare of the public. A culture of empowerment—to ask questions, to be inquisitive—brought the code of ethics to life, and it happened because one person spoke up. Thank you, Diane Hartley.

Culture is all around us—personal, family, and, most impactful to our professional life, the culture that exists within the organizations in which we work and are members. As an engineer, I work for a private company and belong to ASCE and many other organizations. My endeavor to assist in the creation of a new ASCE Code of Ethics consisted of over 24 months of volunteer work that included frequent thoughtful introspection and many group discussions on the concepts of ethics, along with the construct of the new code.

Taking part in this effort led me to the intersection of ethics and culture. The organizations we work for, the expectations they have of us, the key performance indicators that drive our day-to-day activities, and the overall culture impact of how, when, and why we engage our professional code of ethics.

Ethics don't exist in a bubble separated from culture. Instead, the culture within our workplace and professional societies either does or does not empower us to speak up, ask questions, and give feedback. And it is the undercurrent of culture that has the potential to impact decisions we make that affect the health, safety, and welfare of the public.

When you feel the urge that further investigation of a potential problem is necessary, there is sometimes a moment of hesitation. It's in that moment when culture will either empower you to speak up or stay silent. Being part of an empowering culture will help avoid dangerous rationalizations and instead engage the community in an objective investigation of potential problems and solutions.

Many engineering failures result from a compilation of seemingly small decisions where one or more errors were made and/or ethical standards were overridden. Errors will never be removed completely from our practice, as we are human. Unlike errors, the overriding of ethical standards could be eradicated through the proliferation of empowered cultures where engineers are encouraged to talk about challenges and collaborate on solutions to potential problems either within the workplace or through professional organization activities.

It is absolutely cliché to say that one person can make a difference, and it's absolutely true in this context. Engineers can drive culture shifts that empower us and others to talk about potential and ongoing problems. I interact within many sectors in my professional career, including municipal and state agencies, nuclear power companies, the oil and gas industry, and others. A best practice I have noted in some industry sectors is an open-book policy on sharing problems encountered and solved—some with industry-wide forums set up for this purpose.

The same engineering community that drives codes of ethics should take steps to drive a culture of empowerment needed to bring the codes to life. This creates better culture within the organizations that employ engineers. Engineering associations and societies, through national, state, and local levels, should employ and encourage a more open policy on the sharing of engineering problems encountered and resolved, especially as they relate to protecting the safety, health, and welfare of the public.

A code of ethics is a bicycle with no wheels if we do not understand the importance of culture as its close companion and driver of ethical decision-making. Whether it's one engineer working bottom up driving a culture to speak up in the Monday morning meeting within their organization, a national society working top down to drive a culture of empowerment through active engagement with their code of ethics, or through an engineering error forum in monthly chapter meetings, it is critical that we understand and do what we can to drive a culture that brings the code of ethics to life.

Acknowledgments
I would like to thank Robin Kemper for the opportunity to serve on the ASCE Task Committee and the committee members for the process as we endeavored together to create the new ASCE Code of Ethics. Special thanks to Brock Barry and Stephanie Slocum for their contributions to this article.

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