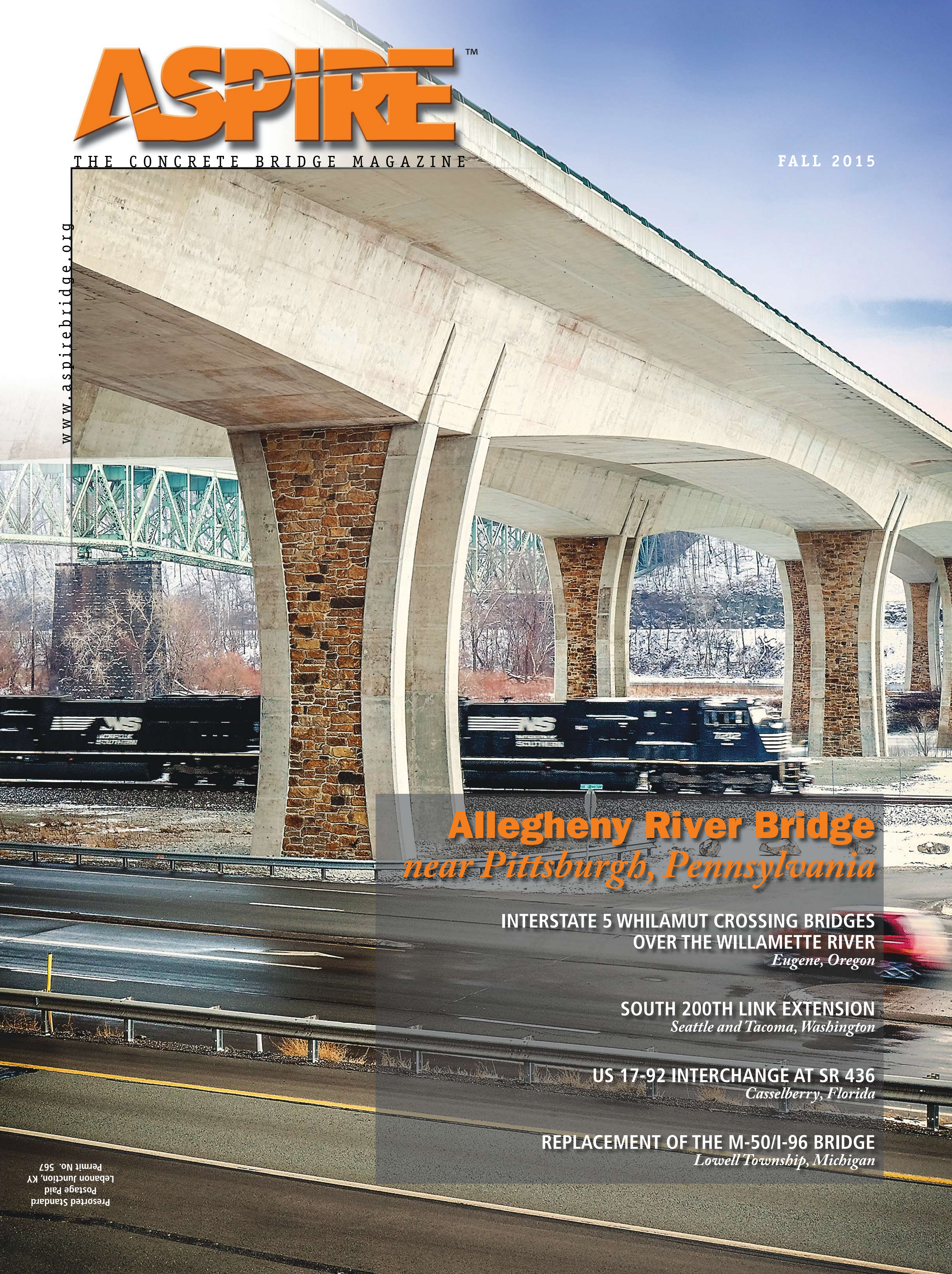

ASPIRE™

THE CONCRETE BRIDGE MAGAZINE

FALL 2015

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Allegheny River Bridge
near Pittsburgh, Pennsylvania

INTERSTATE 5 WHILAMUT CROSSING BRIDGES OVER THE WILLAMETTE RIVER
Eugene, Oregon

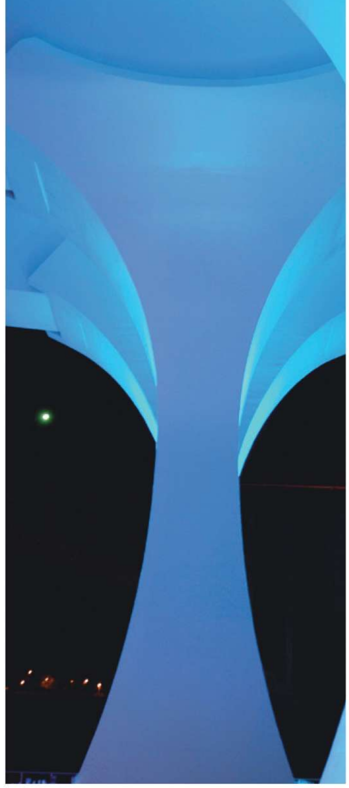
SOUTH 200TH LINK EXTENSION
Seattle and Tacoma, Washington

US 17-92 INTERCHANGE AT SR 436
Casselberry, Florida

REPLACEMENT OF THE M-50/I-96 BRIDGE
Lowell Township, Michigan

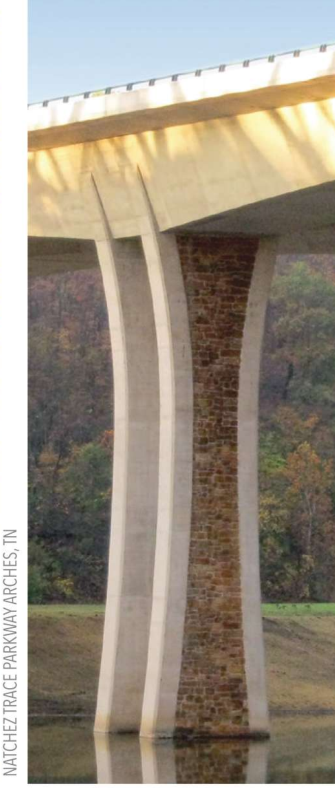
Presorted Standard
Postage Paid
Lebanon Junction, KY
Permit No. 567

I-93 LEONARD P. ZAKIM BUNKER HILL BRIDGE, MA



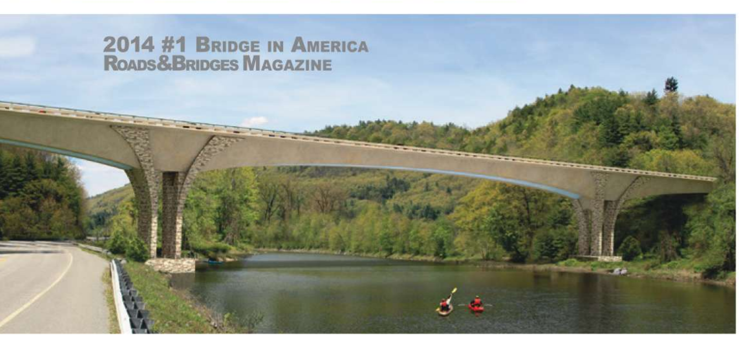
NEW I-35W BRIDGE, MN

NATCHEZ TRACE PARKWAY ARCHES, TN



I-76 ALLEGHENY RIVER BRIDGE, PA

OPENING 2017
SARAH MILDRED LONG BRIDGE, ME
RENDERING



OPENING 2016
I-91 BRATTLEBORO BRIDGE, VT
RENDERING

UNDER CONSTRUCTION
HONOLULU RAIL TRANSIT PROJECT
KAMEHAMEHA HIGHWAY, HI

OPENING 2016
I-90 DRESBACH BRIDGE, MN
RENDERING

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Features

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Photo: Walsh Group.

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Highest and Best Use of Your Time

William Nickas, *Editor-in-Chief*

Today's world has made us more accessible and there is an app for everything. You are expected to fill out your time sheet; fill out an expense report; fill out progress reports; fill out two-week look aheads; review staff utilizations; review backlogs; and reallocate resources from anywhere, and at any time. These are all realities of running a business, but in many companies too much time is being spent "administering" and "tracking" project activities and tasks. Project principals are faced with managing and adjusting a client's expectations and at the same time protecting the technical/production teams from multiple interruptions to allow them to immerse themselves in the exciting job of delivering bridges.

Whether I was working at the farmer's market at my grandfather's produce brokerage house or my dad's construction company, there was a family theme: "Highest and Best Use of Your Time." Every employee knew that family mantra. No salesman was at the copier, no crew foreman was sorting papers into the cubbies for filing, no brick mason was mixing mortar, and certainly everyone understood their specific job tasks.

Has today's connectivity distracted our most valuable and creative employees from being at the optimal level of productivity? We all know that someone has to steer the ship, but come on folks, it looks like everyone is steering and fewer and fewer are rowing the boat. Please position yourself as an expert with a passion for bridges. Do not let distractions consume your energy and certainly guard against a growing tendency of doing more with less, which really means upward delegation of tasks resulting in additional lost opportunity for your most talented staff. Always look for a focus for the day.

Positioning yourself is crucial and identifying your expertise to internal and external customers is a must. When everyone understands each other's strengths, teamwork comes naturally.

As you work toward that next impression, whether a website or an oral presentation, lead off with your ideas and approach. This business requires precision and consistency. Make the audience well aware of the outcomes and ideas about the concrete bridge project rather than a large focus on yourself. Truly some websites need to be flipped around and repositioned.

As I mentioned in the last issue, Emily Lorenz explains in this issue why the regulatory process used in developing transportation projects explicitly meets the balance sought by the sustainability movement, but there is a call for action. There is a higher need for those selecting and creating the built environment to reinfuse why resiliency and high performance are keys to long-life bridges with low maintenance. We don't want to substitute sustainability for resiliency; instead sustainability should encompass resiliency. Please read this important article and pontificate if you really want your college kid to sleep on the 7th floor of a wooden dormitory with sprinklers? I think not. Wood is touted as green, but is it really a high-performance material that also provides safety and resiliency? I know this periodical focuses on bridges, but all new structures need to include considerations for passive resistance to damage and deterioration through better details and material selections. Talk to your neighbors and friends to educate our general communities on these broader structural and construction concepts and help adjust society's expectations and behaviors.

Get on board with the most versatile and intrinsically robust construction material, concrete, and enjoy making every day the highest and best use of your time. I certainly enjoy my career in transportation and the whole *ASPIRE*™ team hopes to create or reignite a passion in you for concrete bridges. Please go to the website and send us your concrete bridge story ideas for editorial board consideration in the near future.

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Cover
Walsh Group built the Allegheny River Bridge, which features twin cast-in-place concrete segmental bridges with 532-ft-long main spans. Photo: FIGG, the engineer of record for the project.

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CONCRETE CALENDAR 2015–2016

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

October 7-9, 2015
2015 PTI Committee Days
Harrah's New Orleans Hotel
New Orleans, La.

October 15-18, 2015
PCI 2015 Fall Committee Days and Membership Conference
Louisville Convention Center
Louisville, Ky.

November 2-3, 2015
ASBI 27th Annual Convention
Omni Dallas Hotel
Dallas, Tex.

November 8-12, 2015
ACI Fall Convention
Sheraton Denver Downtown Hotel
Denver, Colo.

December 7-8, 2015
2015 National Accelerated Bridge Construction Conference
Hyatt Regency Hotel
Miami, Fla.

January 10-14, 2016
Transportation Research Board 95th Annual Meeting
Walter E. Washington Convention Center
Washington, D.C.

February 2-5, 2016
World of Concrete 2016
Las Vegas Convention Center
Las Vegas, Nev.

March 1-5, 2016
2016 PCI Convention and National Bridge Conference at the Precast Show
Gaylord Opryland Resort and Convention Center
Nashville, Tenn.

April 11-12, 2016
ASBI 2016 Grouting Certification Training
J. J. Pickle Research Campus
Austin, Tex.

April 17-21, 2016
ACI Spring 2016 Concrete Convention and Exposition
Hyatt & Wisconsin Center
Milwaukee, Wis.

April 20-22, 2016
2016 DBIA Design-Build in Transportation Conference
Charlotte Convention Center
Charlotte, N.C.

April 24-27, 2016
2016 PTI Convention
Long Beach, Calif.

June 6-10, 2016
International Bridge Conference
Gaylord National Resort & Convention Center
National Harbor, Md.

June 26-30, 2016
AASHTO Subcommittee on Bridges and Structures Annual Meeting
Minneapolis Marriott City Center
Minneapolis, Minn.

July 31-August 4, 2016
AASHTO Subcommittee on Materials Annual Meeting
Hyatt Regency Greenville
Greenville, S.C.

October 23-27, 2016
ACI Fall 2016 Concrete Convention and Exposition
Marriott Philadelphia
Philadelphia, Pa.

November 7-8, 2016
ASBI 28th Annual Convention
Long Beach Convention and Entertainment Center
Westin Long Beach Hotel
Long Beach, Calif.

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*.


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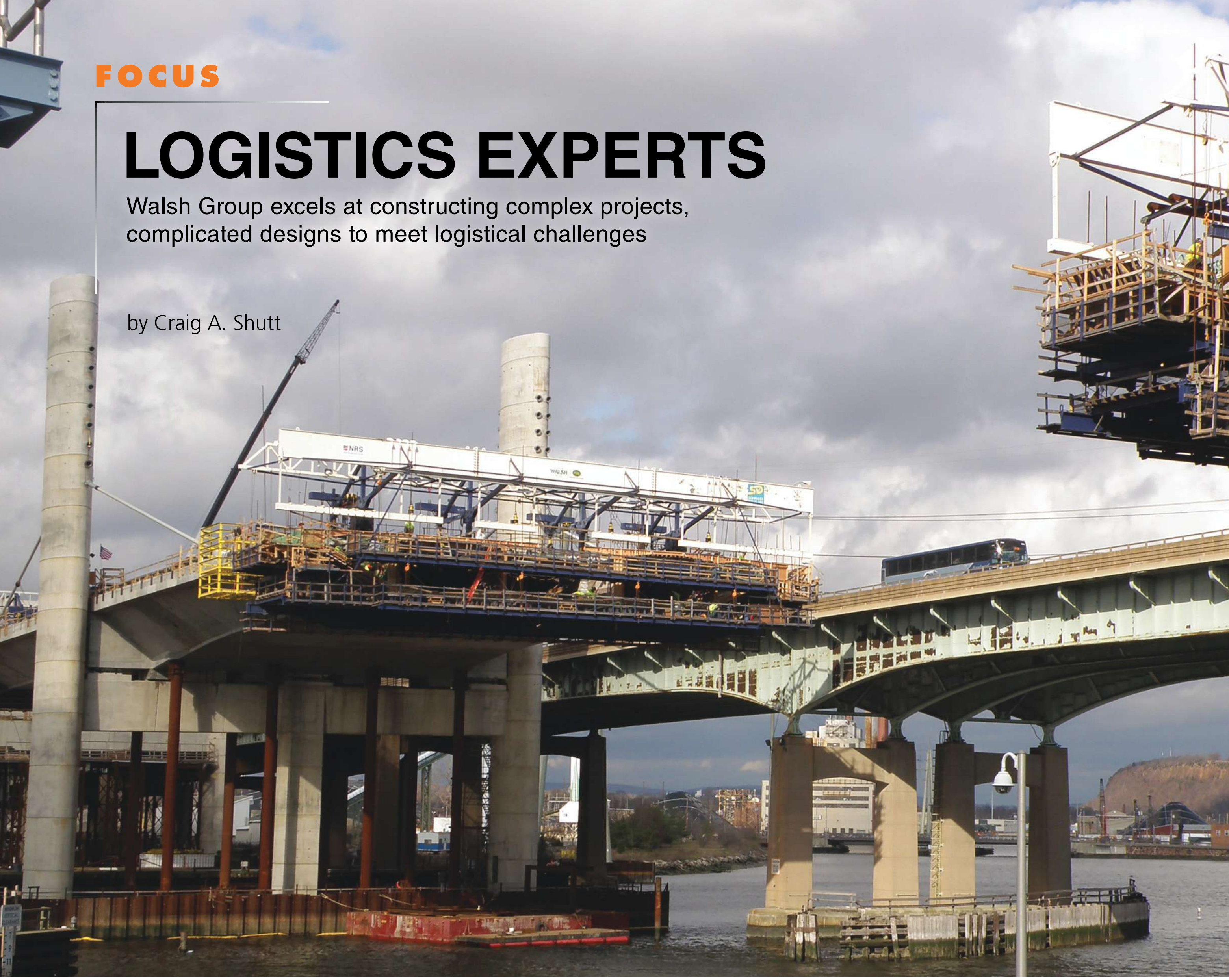
LOGISTICS EXPERTS

Walsh Group excels at constructing complex projects, complicated designs to meet logistical challenges

by Craig A. Shutt



As part of the $1-billion revamp of the highways, the new I-95 Q-bridge features cast-in-place concrete cantilevered segmental box-girder structures. Photo: Walsh Group.

The Walsh Group has gained a reputation for handling complex, signature bridges and creating innovative techniques that influence later designs. But project complexity often goes beyond unique designs to encompass scheduling issues and constructability challenges on major multi-bridge projects. Walsh also excels at those needs, as proven by its recent contract with the Pennsylvania Department of Transportation (PennDOT) to replace 558 bridges in the state by the end of 2017. Nearly all of them will feature concrete designs.

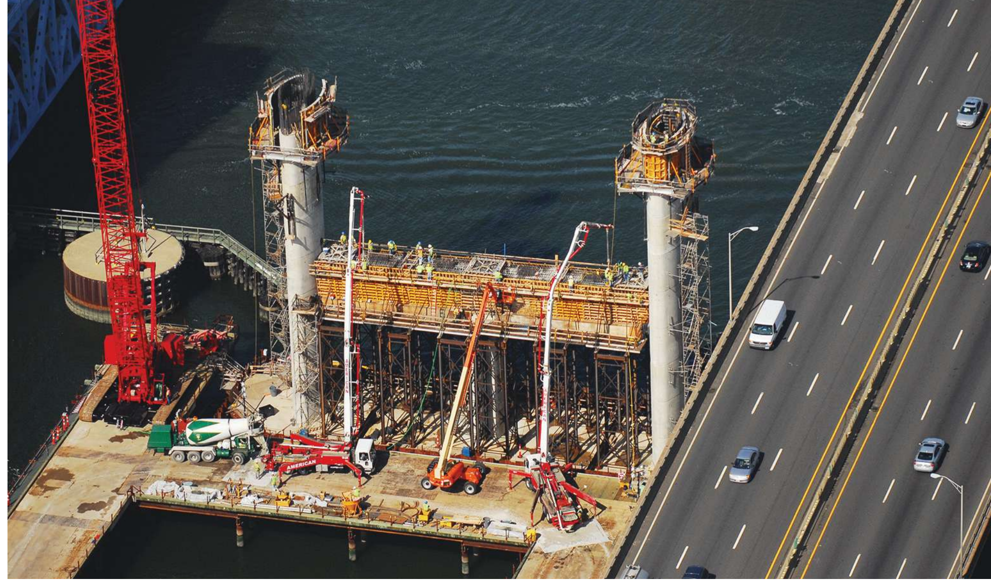
"Our key strength is our ability to execute work for our clients and manage the projects at a practical level every day," says Will Johnson, project manager in the New Haven, Conn., office. "Our company structure allows us to make decisions at the project level rather than go through levels of corporate discussion that can slow down activities. We also have the largest equipment fleet in North America, with a tremendous amount of resources to pull from that gives us an edge over competitors. Those advantages keep us focused on the end product."

PennDOT's P3 Project

These resources are apparent in the PennDOT Rapid Bridge Replacement Project, which was let last October. The public-private partnership (P3) program will replace 558 aging bridges—primarily crossings on smaller state highways and in rural areas—in 3 years. Walsh is part of Plenary Walsh Keystone Partners, comprising Plenary Group, Granite Construction Co., HDR Engineering, and Walsh (Walsh Investors, Walsh Infrastructure Management, and Walsh Construction). The group is not only designing and constructing the bridges, but it is also financing and maintaining them for 28 years.

At least 548 of the bridges will feature concrete beams and concrete box culverts, says Arik Quam, project manager in the Pittsburgh office. Approximately 428 will consist of concrete box girders, spread girders, or I-beams, while about 120 will be composed of precast concrete box culverts.

Walsh's concrete bridge design was a key to their winning proposal, he notes. "As we have to maintain the bridges, we wanted to ensure they were low



The 4649-ft-long I-95 Q-bridge, carries 10 lanes of traffic and features a 1000-ft-long main span. Photo: Walsh Group.

maintenance, and concrete will help with that. We expect fewer long-term maintenance costs with the concrete designs." The size of the bridges—most no larger than 50 ft long and 30 ft wide—played to concrete's strengths. "Concrete offered the most cost-competitive approach. Our goal is to emphasize standardization and create a few basic designs that can be repeated, allowing for rapid construction."

The schedule calls for varying closure times, ranging from 14 to 110 days. For those with 110-day closures, cast-in-place concrete substructures and decks will be used; for those with 35-day closures, the team will use cast-in-place concrete substructures and precast concrete deck panels. On those with 14-day closures, precast concrete components will be erected in 14 days.

PennDOT fast-tracked the program by designating 87 of the bridges for early completion, doing the planning, permitting, utility coordination, and other long-lead activities during the bidding stage. That ensured they were ready for construction when the project was let. "They called it the 'Rapid Bridge Project,' and they wanted to live up to that name," he says. "It let us get shovels in the ground quickly." HDR also has about 20 "squads" of engineers focused on sectors, preparing plans before moving to the next area.

P3 projects like the PennDOT program give Walsh a chance to shine, Quam notes. "We've become very successful with P3 and design-build projects. We do well with complex projects, in both design and logistical applications. We often can be more competitive on that size and type of project."

Johnson agrees. "There are more design-build and P3 projects today, and they work well for us. They allow us to be involved from day one and mitigate any issues early. We can often jump in due to our bonding capacity, which other companies can't match."

Those projects "definitely change how we work," he adds. "When we can partner with the designer, you can understand what the owner wants and give them a more streamlined and efficient design that encourages lower costs. Without those tight relationships between contractor and designer, we couldn't create the efficiencies necessary to do these massive projects in such a short time period."

Speed, Closures Are Key

Owner demands also are rising, focused on two key areas: construction time and road closures. "The public isn't interested in delays," Johnson says. "There is impatience with construction, especially in dense urban areas. Owners don't want construction to interfere with traffic any more than is necessary. And they want it done as quickly as possible."

One example is the company's recent work for the Connecticut Department of Transportation (ConnDOT) on the I-95 Q-bridge, a $417-million, three-span extradosed superstructure bridge over the Quinnipiac River in New Haven, Conn. Part of the $1-billion revamp of the highways, the new structure features cast-in-place concrete cantilevered segmental box-girder structures. The 4649-ft-long bridge, carrying 10 lanes of traffic, features a 1000-ft-long three-span main bridge. The project is phased in three stages to accommodate traffic shifts, keeping traffic moving throughout construction.

"The owners wanted a signature look but the location is near the airport, so we couldn't provide the height that cable-stayed towers would need," Johnson explains. "The extradosed design provided a lower profile and increased the span length over the channel, while also creating a wider design for future maintenance work."

The project was the first extradosed bridge in the United States. "We expect them to become more

The I-4 Lee Roy Selmon Expressway Connector project in Tampa, Fla., features 12 precast concrete segmental bridges plus 11 precast concrete bulb-tee girder bridges and 12 bridges with Florida U-beams or AASHTO I-beams. Photo: Walsh Group.

The precast concrete segments and precast concrete bulb-tee girder bridges of the I-4 Lee Roy Selmon Expressway Connector project use more than 500,000 ft^2 of concrete bridge decks. Photo: Walsh Group.

common," he notes. "It's more cost efficient than other designs. We're bidding more of these now and expect to win some."

Need for Speed

In addition to keeping traffic flowing and meeting unusual terrain requirements, concrete designs also are aiding the need for speed. "We often cast the concrete components alongside the project and then slide in the finished pieces over the weekend."

Walsh's sister company, Archer Western, was one of the first to take this approach, notes Jeffery Will, an estimator and project manager in the Tampa, Fla., office. "In some cases, we can cast new superstructure elements and reinforce the pier caps to give the bridge new life." Lightweight concrete has been aiding this effort, he notes, reducing weights by as much as 40% on some projects and speeding construction.

Although replacement and rehabilitation projects account for much of the company's work, new structures continue to be commissioned—and are enjoyed. "I love brand new, open-field jobs," says Will. "You're unlimited in your approach and where you can work. If there's an issue, you can move crews to another area until it's resolved. It can create logistics problems to jump out of sequence, but the work doesn't have to be linear when it's not a replacement project that travelers are counting on."

New projects alleviate concerns about unknown foundation problems or undocumented materials in buried temporary works. "By far, new projects are much better because there are so many fewer unknowns."

Archer Western put these ideas into practice for the I-4 Lee Roy Selmon Expressway Connector project in Tampa, Fla., on which Will served as deputy project manager. The $405-million road and bridge project created a 1-mile-long connector consisting of 12 precast concrete segmental bridges made of 2765 precast segments using balanced-cantilever and span-by-span construction plus 11 precast, pretensioned concrete bulb-tee girder bridges and 12 bridges with Florida U-beams or AASHTO I-beams. The work was completed in one phase, but there were also tie-ins requiring four minor phases, which involved 29 precast concrete mechanically stabilized earth walls and other ancillary construction.

Joint Ventures Growing

The Tampa project, like the Q-Bridge and others, was done in a joint venture (with PCL), which Walsh has been participating in more often, Will notes. "The jobs have gotten larger and everyone wants to share the risk, so they are looking at partner options more often," he explains. Walsh was reluctant to enter such partnerships in the 1990s, he notes, as several bad experiences caused the owners to back away. In the early 2000s, Walsh returned as the primary sponsor. "After a while, we put our toe in the water to reciprocate with some of our previous partners to serve as the minority partner."

PCL made a perfect partner, he adds, due to previous work with the firm in the Northwest, on which Walsh served as the sponsoring firm. "They suggested teaming up, and it made sense. They have a lot of experience with precast concrete

The 2765 precast concrete segments and 11 precast concrete bulb-tee girder bridges were used for the I-4 Lee Roy Selmon Expressway Connector project. Photo: PCL Civil Constructors and Archer Western Construction, joint venture.

The Mon River Bridge 51H near Brownsville, Pa., features a contractor alternate design created by FIGG Engineering Group consisting of dual-cell concrete box girders. Photo: Walsh Group.

segmental designs and are based in Tampa." Many joint ventures begin as conversations at conferences and other meetings, where executives talk about upcoming projects, he notes.

Officials at the Florida Department of Transportation offered four options for the project: steel tub girders, steel tub girders with precast concrete I-girders, precast concrete segments, and spliced precast concrete I-girders. They chose concrete segments and concrete girders. "It's really easy on a project like this to plunk in Florida I-girders. It was the least expensive option by far."

Value Engineering Concrete

Many projects are being bid in concrete, even as steel prices decline, due to concrete's efficiency. "Overall, we're doing more concrete projects. With every project, it seems concrete is trumping steel. Many times, we look at a design and ask if we can replace it with concrete. We're finding we can, and it's more economical. We haven't converted any concrete projects to steel, but we do convert steel projects to concrete." The Florida I-beams especially make that efficient. "Every chance we get, we're using Florida I-beams and stretching their spans to the maximum to save substructure work."

Value engineering often creates efficiencies, as happened with the $95.6-million Mon River Bridge 51H near Brownsville, Pa. The 3200-ft-long bridge features a cast-in-place concrete segmental design that was erected in mountainous terrain. The structure carries the Mon/Fayette Expressway over the Monongahela River, Norfolk Southern Railroad, SR 4022 Labelle Road, and SR 2026 Main Street. It includes a 518-ft-long main span consisting of cast-in-place concrete, dual-cell box girders. The seven-span bridge has piers ranging in height from 100 to 206 ft.

FIGG Engineering Group and Walsh suggested a contractor-alternate design when they realized that the repetitive casting of the segments could save significant costs—$8 million in all. "We took on the risk, but we knew the concrete design would be more cost competitive," says Quam. Savings especially accrued by erecting concrete components high in the air. "That played to concrete's strengths. It would have been costly and complicated to erect big steel members that high in the air over water."

Walsh used its experience on an earlier project, the Allegheny River Bridge near Pittsburgh, Pa., as a template for the Mon/Fayette Expressway project. It consisted of dual bridges carrying the Pennsylvania Turnpike over the Allegheny River, Allegheny Valley Railroad, Canadian National Railroad, and SR 1008. The project consists of twin 2350-ft-long, cast-in-place concrete segmental designs constructed with the balanced cantilever method (its first use in Pennsylvania) and features a 532-ft-long main span.

Value engineering to concrete occurs more often today, says Will. "There are a lot of challenges out there, but we find most can be met if we gravitate to concrete. It provides a lot of possibilities. There are very few times that we need to go to steel."

Savings in time, money, and travel delays will continue to be the focus at Walsh. "Every company has talented people," Johnson says. "But we encourage ours to think outside the box to help the owner overcome design issues. We want to resolve any constructability issues as soon as possible to everyone's benefit and create a cost-effective structure."

The six-span Allegheny River Bridge, the first segmental concrete box-girder bridge in Pennsylvania constructed with the balanced cantilever method, used nearly 50,000 cubic yards of concrete and more than 3 million pounds of post-tensioning. Photo: Walsh Group.

117 Years of Experience

The Walsh Group, a 117-year-old company headquartered in Chicago, Ill., is currently in its fourth generation of family leadership. The Walsh Group is ranked as one of the nation's top 15 contractors, according to *Engineering News-Record*, as well as the largest bridge builder and the fourth largest firm among Transportation Sector Contractors. The company maintains a national presence within the industry through 19 regional offices.

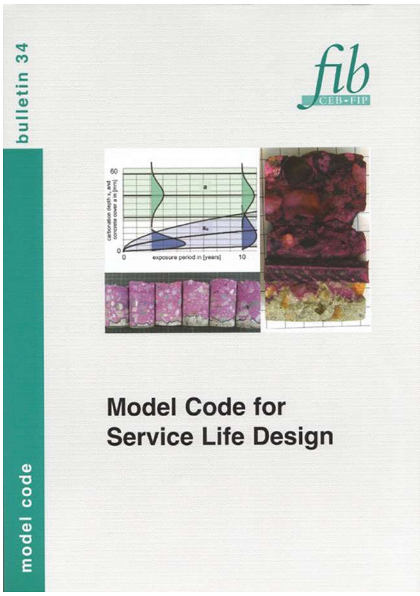
The Walsh Group provides general contracting, construction management, and design-build services through subsidiaries Walsh Construction and Archer Western.

EDITOR'S NOTE

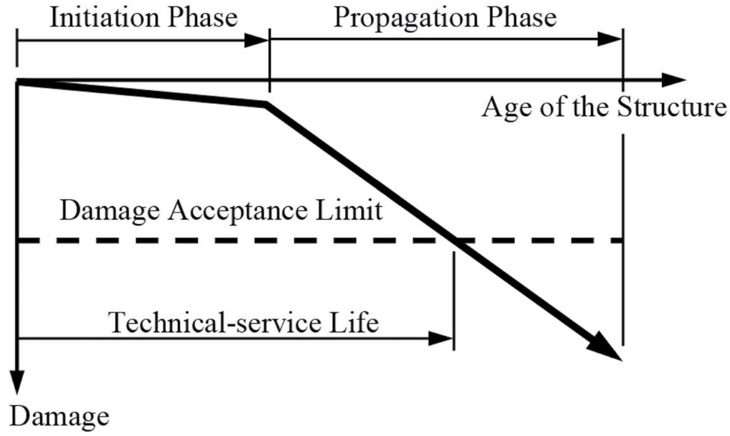
The I-4 Lee Roy Selmon Expressway Connector project, the I-95 Q-bridge, the Mon River Bridge 51H, and the Allegheny River Bridge were featured in the Fall 2013, Fall 2012, Fall 2011, and Spring 2009 issues of ASPIRE,™ *respectively.*

Are We Really Designing for a 100-Year Service Life?

by Mike Bartholomew, CH2M Hill



fib Model Code for Service Life Design (Bulletin 34). Figure: *fib*.



Two-phase deterioration model for reinforced concrete due to corrosion. Figure: Mike Bartholomew.

Recently, requests for proposals for several large bridge projects have had requirements for the structure to have a service life of 100 years. With no U.S. standards or guidelines in place to establish performance criteria for service life design (SLD), it is often unclear what is being requested and what is being achieved.

SLD for concrete structures has developed over the past 30 years in Europe, and has been documented in several international standards and specifications:

- *Model Code for Service Life Design* by the International Federation of Structural Concrete (*fib*) (Bulletin 34)
- *Model Code for Concrete Structures 2010* by *fib*
- *Durability—Service Life Design for Concrete Structures* (ISO 16204) by the International Standards Organziation (ISO)

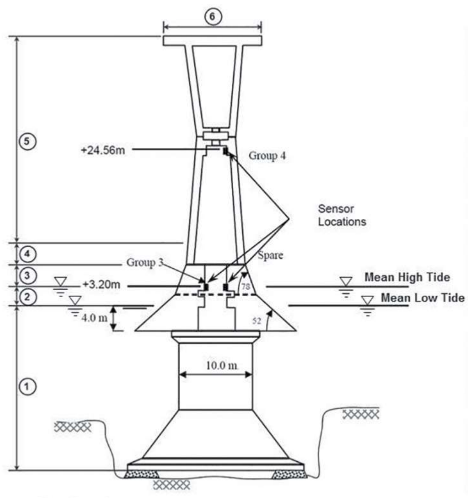
In the United States, SHRP2 research project R19A, "Service Life Design for 100 Years and Beyond," was completed in 2013. Currently, the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) are sponsoring the SHRP2 R19A Implementation Action Program to promote the use of SLD. Four state departments of transportation (Iowa, Oregon, Pennsylvania, and Virginia), along with FHWA Central Federal Lands Division, are developing bridge projects using SLD principles. As these projects are completed, training materials will be developed and published to show the need for using SLD.

SLD is based on the way materials deteriorate in their environmental exposure conditions. Concrete structure deterioration is generally due to corrosion of the reinforcing steel. Chlorides from seawater or deicing chemicals represent the most severe environmental exposure zones. Other deterioration mechanisms include reinforcement corrosion after concrete carbonation, concrete damage due to alkali-silica reaction, and abrasion on bridge decks.

Chloride ingress deterioration has been well defined. Chlorides applied at the surface of the concrete diffuse with time through the outer concrete cover layer. When chloride ions reach a critical concentration threshold at the level of the reinforcement, corrosion initiates. Corrosion by-products are expansive, and coupled with concrete's low tensile capacity, this expansion creates surface cracking. As the corrosion continues, it leads to spalling and loss of steel cross section. The deterioration mechanism consists of two phases:

- An **initiation** phase, where there is no visible physical change to the structure
- A **propagation** phase, where the structure experiences damage from corrosion

A mathematical model based on Fick's 2nd Law for diffusion, outlined in *fib* Bulletin 34, defines the initiation phase. Currently, there are no generally accepted models for the corrosion propagation phase. Fick's 2nd Law can be evaluated as a load and resistance factor equation similar to traditional structural design.



Component	Figure ID	Exposure Class (EN206)*
Substructure		
Submerged Zone	1	XS2
Tidal Zone	2	XS3
Splash Zone	3	XS3
Spray Zone	4	XS3
Atmospheric Zone	5	XS1
Superstructure		
Atmospheric Zone	5	XS1
Roadway & Traffic Barrier	6	XD3

*Source: BS EN 206: 2013 *Concrete. Specification, performance, production and conformity.*

The environmental exposure of the structure and its components can be accomplished with the use of a structure exposure category diagram. Figure: Mike Bartholomew.

The environmental loads are the chloride concentration applied at the surface of the concrete, the initial chloride content of the concrete, and the average temperature at the bridge site. The parameters that define the durability resistance of the concrete are the chloride diffusion coefficient and the depth of cover to the reinforcement. The diffusion coefficient is affected by the mixture proportions, particularly water-cement ratio, and the presence of supplementary cementitious materials. The limit state is defined by the chloride threshold of the steel reinforcement.

SLD strategies are divided into two classes:

- **Avoidance of Deterioration:** A strategy where materials are provided that have resistance well beyond the requirements needed. For example, use of stainless steel reinforcement, which has a chloride threshold many times that of conventional reinforcement.
- **Design Based on Deterioration from the Environment**, which is subdivided into three levels:
  - *Full Probabilistic*—Uses mathematical models such as Fick's 2nd Law, where the environmental demand and resistance parameters are represented by mean values and distribution functions (standard deviations and the like), and a probabilistic, Monte-Carlo type analysis to compute the level of reliability.
  - *Deterministic*—Uses the same mathematical models as for the full probabilistic approach, but with load-and-resistance factors applied to the environmental demands and durability resistance parameters. This results in a direct solution to the model. The current state of the practice has insufficient data to develop load and resistance factors to a level of reliability satisfactory for general use.
  - *Deemed to Satisfy*—A prescriptive approach where concrete materials and cover dimensions are specified in code provisions. The *AASHTO LRFD Bridge Design Specifications* includes cover dimensions, but does not correlate them to concrete durability parameters or environmental exposures, resulting in a very low level of reliability.

Different SLD strategies may be applied to different components of the structure. For certain types of deterioration like alkali-silica reaction, no mathematical models currently exist. For these, avoidance may be the only choice.

Performing SLD on new bridges will require a systematic change in the way we perform our work, not only in design, but during construction and through operation during the life span of the structure. This process consists of the following steps:

1. Identify the environmental exposure of the structure and its components. This can be done graphically.
2. Select a limit state and an expected service life. Current practice is to define the end of the initiation phase as the limit state. This does not mean that the structure is no longer usable; rather that it has reached a condition where major repairs are required to allow safe operation. The 100-year service life typically applies only to main structural components of the bridge. Components like bearings, expansion joints, and overlays may need to be replaced periodically over the structure's life.
3. Define a SLD process and performance criteria, such as *fib* Bulletin 34 for the full probabilistic method with a probability of achieving the limit state of 90%.
4. Select concrete materials and cover dimensions to satisfy the design requirements. Concrete mixture proportions are identified at this time to establish target chloride diffusion coefficients for design.
5. Produce contract documents. Testing for the chloride diffusion or migration coefficient has not been part of standard tests used in the United States. Tests, like Nordtest NT Build 492, performed at 28 days like concrete strength tests, need to be introduced into the standard specifications.
6. Perform the same tests in the field during construction to verify that the design intent has been met. This also includes concrete cover dimension mapping after the concrete has been cast.
7. Inspect and maintain during operation. This is imperative to ensuring that the service life can be realized.

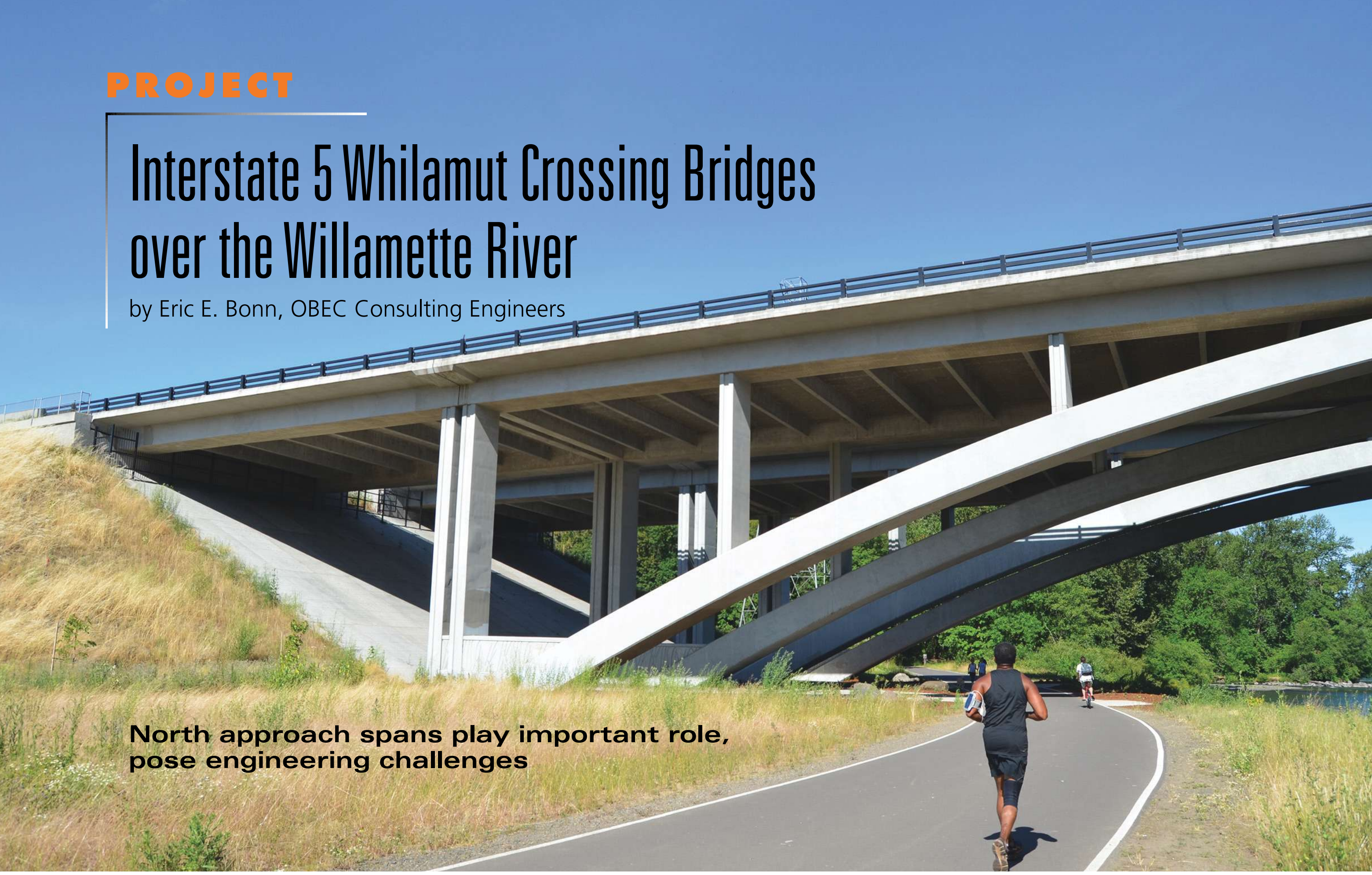
Following the above process provides a rational, scientific approach to achieving a specified service life. This entire process is not complex, but is new to owners, designers, and contractors. It will require training, but it can be and needs to be achieved.

PROJECT

Interstate 5 Whilamut Crossing Bridges over the Willamette River

by Eric E. Bonn, OBEC Consulting Engineers

North approach spans play important role, pose engineering challenges



Approach span and start of arch span showing path going underneath. All Photos: OBEC Consulting Engineers.

It can be easy to overlook the 84-ft-long north approach spans in these nearly 2000-ft-long bridges, especially when the main spans are the award-winning arches of the Interstate 5 (I-5) Whilamut Crossing Bridges over the Willamette River in Eugene, Ore. However, these apparently straight-forward, utilitarian structures incorporated several unique engineering aspects. The design and construction of the main spans are detailed in an article in the Summer 2012 issue of *ASPIRE*.™

Bridge Type Selection

Span 1 of Whilamut Crossing Bridges land on the north bank of the Willamette River within the limits of the city of Eugene's Alton Baker Park. The approach roadway is on earth fill. The span's two arches are founded near the riverbank and have one of the major park trails running under them. Span 1 is the transition between the approach fill and the arch spans.

Various alternatives were considered for this transition, including retaining walls and precast concrete box or bulb-tee girders. Typical mechanically stabilized earth (MSE) walls could have eliminated the need for the span 1 structure. However, the mass of the 40-ft plus tall MSE wall that would be required was not in keeping with the light and airy appearance of the arch spans and would visually close in the recreational path corridor.

Standard Oregon Department of Transportation (ODOT) precast, prestressed concrete box girders or bulb-tee girders could support the span, but the transition between the precast concrete approach span and cast-in-place concrete main spans was determined to be visually unappealing and not in keeping with the clean, repetitive pattern desired.

To best combine span 1 with the rest of the structure, it was designed to mimic the adjacent main spans. In the arch spans, the main elements supporting the deck structure are longitudinal T-beams that are supported by spandrel columns springing from the arch ribs. The 10-in.-thick deck spans about 11.75 ft longitudinally between transverse floor beams that frame into the T-beams. The 6.75-ft-wide deck overhangs are supported directly from the T-beams. The floor beams are 40-ft-long, 10-in.-wide, and 2-ft 9-in.-deep precast, prestressed concrete rectangular sections. The same floor

profile

INTERSTATE 5 WHILAMUT CROSSING BRIDGES OVER THE WILLAMETTE RIVER / EUGENE, OREGON

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

PRIME CONTRACTOR: Hamilton Construction, Springfield, Ore.

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

PRECASTER: Knife River Prestress, Harrisburg, Ore.—a PCI-certified producer beam design was used in span 1 as in the main arch spans. While details, such as number of spans and span lengths of the entire northbound and southbound structures vary slightly from each other, span 1 dimensions and details were the same for both the northbound and southbound bridges.

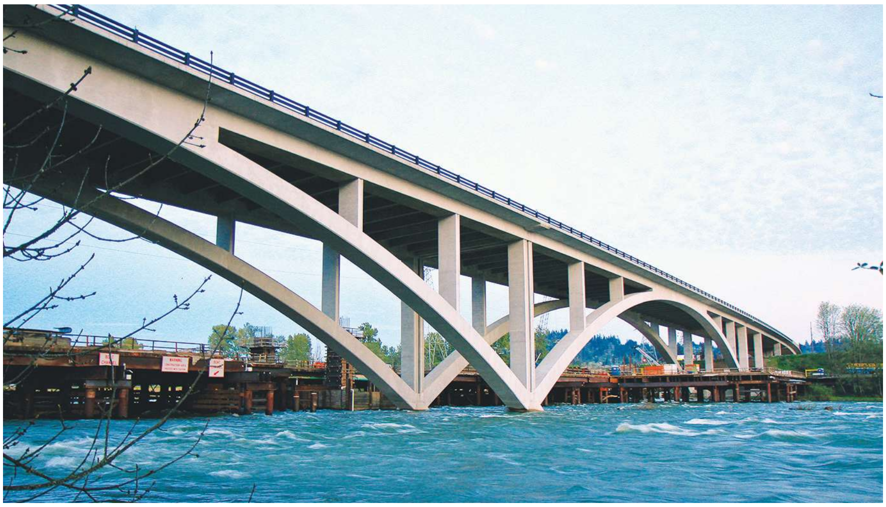
The T-beam stems are 7 ft wide, only 5 ft deep, and are spaced 47 ft apart under the 64.5-ft-wide deck. The typical column-to-column span of the T-beams in the arch spans is under 50 ft. This allowed the T-beams to act continuous over their entire length and be conventionally reinforced. The 82-ft-long, simple-span condition of span 1 exceeded the ability of mild-steel reinforcement to adequately support the structure, therefore post-tensioning was added. Each T-beam has four tendons with twenty-three, 0.6-in.-diameter strands. All tendons were tensioned from the abutment end of the span for ease of construction because friction losses were low over this short span.

Design Considerations

Typical design considerations related to the post-tensioning had to be considered including bending stresses, ultimate moments, and shears. Special consideration was given to the tensioning order, anchor set, bursting reinforcement in the deck, effective flange width, and the configuration of the bent 2 anchor zone.

The 47-ft spacing of the T-beams created a long lever arm and necessitated the tendon stressing to alternate between the left and right beams to limit superstructure bending about the vertical axis. A limit was set that no more than ⅙ of the total prestressing force could be eccentric about the bridge centerline at any time based on a stress analysis of the deck overhangs.

Setting the anchor locations at the centroid of the T-beam sections—to eliminate prestress tensile stresses at the ends of the spans, accommodate the shallow 5 ft height of the member, and provide the minimum possible offset of the strands from the beam soffit—resulted in the drape of the post-tensioning strands being limited to approximately 2.5 ft. The prestress losses due to friction were low due to the limited angular change in the strand path. While this was beneficial to the strength of the T-beams, it caused the length of the anchor set loss to extend nearly to the opposite end of the span, which would undesirably reduce the strand stress at the dead-end anchorage. Limiting the anchor set to a low value of ⅜ in., which is less than the ODOT standard procedure of ½ in., prevented the stress loss from reaching the far anchor.



Completed southbound I-5 Whilamut Crossing Bridge looking toward south approach spans, with northbound work bridge in the background.

Typical strut-and-tie methodologies were employed to distribute the jacking force first into the T-beam stem and then into the deck. The results of these analyses indicated large tensile forces would be generated in the deck just inside the anchorages as the post-tensioning forces tried to distribute inward toward the centerline of the bridge. A two-dimensional finite element model using plate or shell elements was created to verify that the strut-and-tie model layout closely approximated the actual distribution of forces in the deck. An additional 24 transverse No. 11 bars were required to resist these tensile forces.

The effective flange width of the deck due to the wide spacing of the T-beams was a concern. In the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*, the effective flange width for an exterior beam is allowed to be the sum of the deck overhang, girder, and one half of the spacing to the adjacent girder. The minimum span-length-to-girder-spacing ratio investigated in developing this provision was 3.1. The corresponding ratio for this bridge is 1.7, so it wasn't prudent to use half the deck width (32.25 ft) as the effective flange. Instead, a conservative estimate of approximately 21.75 ft, similar to the previous limit of one-quarter of the span length, was used in the flexural stress and moment checks.

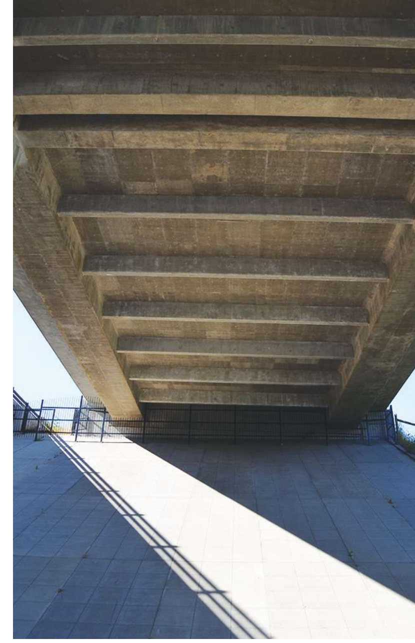
The last design issue of concern was the configuration of the dead-end anchorages at bent 2. Because the T-beams were located directly over the columns and there was no beam

OREGON DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: Each north approach span consists of two simple span, cast-in-place, post-tensioned T-beams with a span of 82 ft.

STRUCTURAL COMPONENTS: Each structures consists of two 7-ft-wide, 5-ft-deep T-beams with precast concrete transverse floor beams spanning between them.

View of the north approach span.



Soffit view of approach span showing T-beams and floorbeams.

Arch and approach span falsework for the I-5 Whilamut Crossing Bridges.

Approach span falsework and formwork plus bent 2 column reinforcement.

overhang past the column, the post-tensioning anchorage trumpets were in direct conflict with the vertical reinforcing bars extending from the column. The longitudinal reinforcement in the transverse end beam also contributed to the congestion. Seismic design requirements called for the full development of these bars within the T-beam so plastic hinging would occur within the column.

Bar development was achieved through careful placement of the vertical reinforcement, and limited use of hooked bars or headed reinforcement. Multiple reinforcement details were included in the project plans for just this one location to clearly indicate the design intent.

The specified concrete compressive strength for the T-beams and deck was 5.0 ksi, which is the minimum concrete strength allowed by ODOT for prestressed concrete members. ODOT's high-performance mixture proportion modifications, which requires a fraction of the portland cement to be replaced with supplementary cementitious materials, such as silica fume and fly ash, were used for the deck concrete for increased durability. Maximum aggregate size in both the T-beams and the deck was ¾ in.

Construction

Construction of the T-beam stems used conventional falsework supported off the ground. The dead and prestressed loads were balanced to the extent that only ⅛ in. of camber was required in the formwork. The stem falsework also held the precast concrete floorbeams in place so their extended strands and reinforcement could be cast into the stems. The deck falsework between the T-beams was suspended by hangers attached to the floorbeams while brackets mounted on the T-beam stems carried the deck overhang formwork.

Once the deck was cast and cured, the post-tensioning was applied and all the falsework and formwork removed. After the tendon grouting was complete, the post-tensioning anchor blockouts were filled and bridge rails and joints were installed. Span 1 construction for the southbound and northbound bridges occurred in 2011 and 2012, respectively, with no significant complications over a period of about 6 months. Because this work was only a small portion of the overall project that was paid for on a lump-sum basis under a construction manager-general contractor arrangement, the construction cost of span 1 is unavailable.

Summary

While only a fraction of the total length of the Whilamut Crossing Bridges, the span 1 structures had their own share of technical challenges and played an important role in the overall coherent appearance of the project.

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

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

EDITOR'S NOTE

The Summer 2012 issue of ASPIRE™ *included a project story on the southbound and northbound main-span bridges carrying Interstate 5 over the Willamette River, at that time called the I-5 Willamette River Bridges.*

AESTHETICS
COMMENTARY

by Frederick Gottemoeller

In the Summer 2012 issue of *ASPIRE*,™ I commented on the aesthetics of the I-5 Whilamut Crossing Bridges over the Willamette River in Eugene, Ore. I concluded my comments with "This bridge ……. creates a memorable visual effect by contrasting its precise geometry and extreme transparency with its natural surroundings, and by inserting only those few physical elements required to do its job. It is a wonderful expression of what we now can do with the high-performance materials and advanced analytical techniques of the twenty-first century. Let's hope it becomes a frequently imitated model for the future." With that in mind, it was very rewarding to see the designers apply the same ideas to the north approach structures.

Too often owners and designers decide, in the name of saving money, to make the shorter approach spans different structural types than the main spans. On very long bridges, where the approach spans are a tiny fraction of the total length and/or are much lower than the main spans, this may not be noticed. That is not the case for the I-5 Whilamut Crossing Bridges over the Willamette River. The approach spans are a significant fraction of the total length and are similar in height to the main spans. Plus, the main spans have a distinctive and attractive appearance. Changing the structural type or especially substituting a mechanically stabilized earth wall would have made for a jarring contrast that would have diminished the original project. Any money saved would have had to be measured against the intangible but real costs of imposing an eyesore on the community. Fortunately, this designer and owner decided to keep the same high quality in the approaches as are in the main spans.

"Unity" is an important aesthetic value. It means that all parts of a project that can be seen at one time have a self-similarity such that they appear to have come from the same mind. It may come from a similarity of structural type, of element shapes, of materials, colors or textures, or some combination of the above. (One frequent practice that diminishes unity is mixing different pier shapes in the same bridge.) The clearer and stronger the appearance of unity, the more attractive and memorable the bridge will be. The I-5 Whilamut Crossing Bridges over the Willamette River take advantage of that fact.

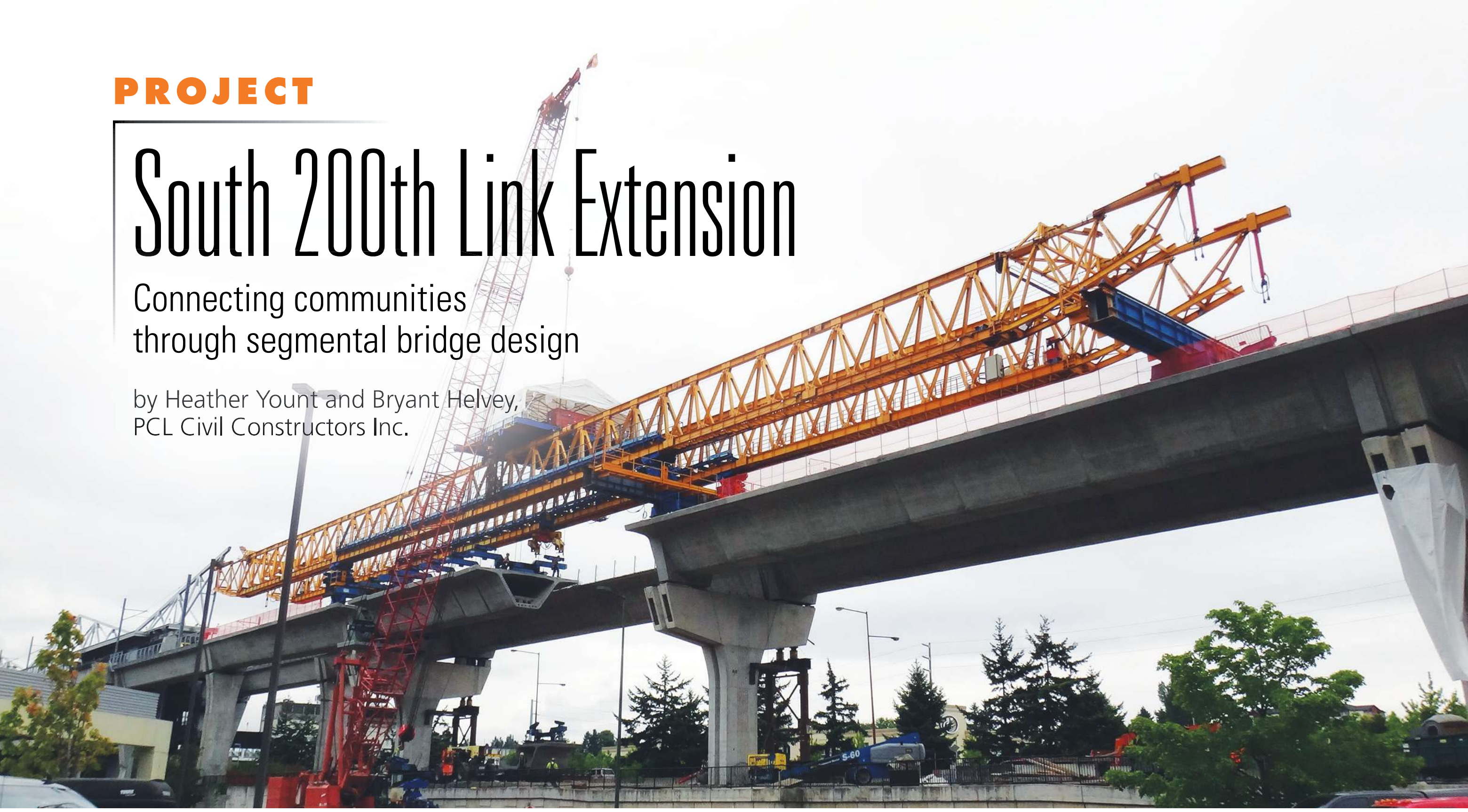
Frederick Gottemoeller is an engineer and architect who specializes in the aesthetic aspects of bridges and highways. He is the author of Bridgescape, *a reference book on aesthetics and was deputy administrator of the Maryland State Highway Administration.*

PROJECT

South 200th Link Extension

Connecting communities through segmental bridge design

by Heather Yount and Bryant Helvey, PCL Civil Constructors Inc.



Installation of the last segments of the South 200th Link Extension. Photo: PCL Civil Constructors Inc.

As the first design-build light rail project for Sound Transit, the South 200th Link Extension lengthens the existing light rail system by 1.6 miles. The project extends the light rail from the Seattle-Tacoma International Airport south to the new Angle Lake Station at South 200th Street. The project comprises 1166 precast concrete segments, each weighing between 35 and 55 tons.

The project team used both balanced cantilever and span-by-span erection methods to assemble the units into an elevated guideway. The 10-ft-long segments were assembled into bridge spans with epoxy joints and 0.6-in.-diameter, post-tensioning strands in tendons stressed to 1000 kips.

The typical span-by-span unit is 27 ft wide and contains 13 segments, forming one span of guideway wide enough for two trains to pass side by side. The balanced cantilevers are up to 40 segments long (spanning 360 ft) and two segments wide, providing a 54-ft-wide structure that allows trains to switch tracks, and a third storage track between the two running tracks.

From Fast-Track to Precast

In choosing the design-build procurement method, Sound Transit and the design-build team were able to create efficiency in the design process by providing comprehensive design and construction services through a single point of contact. The design-build approach also allowed Sound Transit to fast-track the project by beginning construction before the total design was complete; thereby, reducing the schedule by nearly 6 months.

The term accelerated bridge construction (ABC) applies to a multitude of construction techniques, all used with the intention of reducing impacts to the environment, community, and traffic while positively affecting the project's budget and schedule. The practice of using precast concrete segments as opposed to the more traditional cast-in-place concrete superstructure is one way in which Sound Transit benefited from the use of ABC methods.

The use of precast concrete segments enabled the project team to minimize disruptions to vehicular traffic exiting the airport because the segments were manufactured and stored at an off-site casting yard until it was time to erect them. The simultaneous construction of the guideway's substructure

profile

SOUTH 200TH LINK EXTENSION / SEATTLE AND TACOMA, WASHINGTON

BRIDGE DESIGN ENGINEER: HDR Engineering Inc., Bellevue, Wash.

BRIDGE DESIGN SUB-CONSULTANT: International Bridge Technologies Inc., San Diego, Calif.

PRIME CONTRACTOR AND SEGMENT PRECASTER: PCL Civil Constructors Inc., Seattle, Wash.

POST-TENSIONING CONTRACTORS: PCL Civil Constructors Inc., Seattle, Wash., (superstructure) and Schwager-Davis Inc., San Jose, Calif. (substructure)

POST-TENSIONING SUPPLIER: Schwager-Davis Inc., San Jose, Calif., and Dywidag Systems International, Long Beach, Calif.

OTHER CONSULTANTS: KPFF Consulting Engineers, Seattle, Wash., station structural design

Crews prepare to launch the gantry to the next span. Photo: Roger Marble Photography.

Using an overhead gantry, the project team constructed an average of two spans per week. Precast concrete segmental construction allows project teams to maintain a fast pace, shorten the overall project schedule, reduce impacts on the community and other stakeholders, and create a safer work place. Photo: Roger Marble Photography.

components and the concrete segments resulted in a significant reduction to the overall project schedule when compared with more traditional cast-in-place bridge construction techniques. The contractor conducted an analysis of the cast-in-place concrete method versus the precast concrete segmental method and estimated that the precast segmental method reduced the project's schedule by 4 to 6 months.

The project team at the casting yard, located 30 miles from the main site, placed concrete for the bridge segments with a high-strength mixture that provided a concrete compressive strength of 6.5 ksi at 28 days. The mixture was designed to achieve 80% of the 28-day strength in just 12 hours to allow removal from the segment molds. A variety of segment bed forms were used for the bridge components, including four typical segment beds, a pier segment bed, a constant depth bed, and a variable-depth bed. The variable-depth bed cast segments between 8 and 16 ft deep, giving the balanced cantilevers their arched appearance.

The pier segments weighed up to 55 tons and transferred the structural load from the typical segments to the substructure. The pier segments contained the majority of the post-tensioning anchorages, access doors, and pintle bearings. The use of a casting yard helped the project to rapidly produce the segments for the superstructure and created a consistent, quality product after each concrete placement, which reduced the overall project cost.

Precast concrete segments enabled the project team to minimize disruptions to vehicular traffic exiting the airport.

SOUND TRANSIT, OWNER

OTHER MATERIAL SUPPLIERS: Deal Srl, Italy, precast concrete superstructure formwork and erection gantry; Gerdau Steel, Auburn, Wash., reinforcing steel; D.S. Brown Company, North Baltimore, Ohio, bridge bearings; R.J. Watson Inc., Alden, N.Y., bridge bearings; US Spec, Denver, Colo., post-tensioning grout

BRIDGE DESCRIPTION: A precast, post-tensioned concrete, segmental box girder bridge with 1.6 miles of double-track light rail, twin-track, and single-track box girders, with span lengths ranging from 99 to 363 ft

STRUCTURAL COMPONENTS: 66 cast-in-place concrete columns on drilled shafts; four double-leaf, long-span columns on spread footings; four cast-in-place concrete pier tables; 18 cast-in-place concrete pier caps; 1166 precast, post-tensioned concrete segments; 896 post-tensioning tendons; 1.98 million ft of 0.6-in.-diameter steel strand; 14,500 bags of post-tensioning grout

BRIDGE CONSTRUCTION COST: $172.8 million

The project team worked throughout the night to accelerate bridge construction over the roadway. This system allowed the team to complete a month or more's worth of work in one night. Photo: Francis Zera, Zera Photography.

The design-build team worked to develop a balanced cantilever solution that eliminated columns, significantly reducing the number of traffic detours, all while providing a more efficient and durable solution. Photo: PCL Civil Constructors Inc.

Reducing Impacts to Stakeholders

Design-build delivery and ABC methods benefit project owners and stakeholders by reducing project costs and overall construction duration, so it's only sensible that combining the two multiplies the benefits offered.

With more than 34 million passengers traveling through the Seattle-Tacoma International Airport each year, the project team carefully considered construction means and methods that would minimize impacts to airport operations. To reduce impacts to the airport's most heavily congested areas, balanced-cantilever spans were stretched to 360 ft between some piers, and ground-based track cranes were lifted onto the bridge to erect the structures, allowing the segments to be lifted in areas of limited space.

In one instance, the project team combined the balanced-cantilever and gantry erection methods at a temporary pier location, which allowed the team to erect the 210-ft span above the main airport traffic exit and keep the existing walkway open 16 hours per day. The team then removed the temporary support before Memorial Day 2015 so that pedestrians could access the airport's facilities unimpeded.

The project team used a self-launching overhead gantry to erect the precast concrete segments, a method that reduced ground disturbances and the number of road and lane closures. The use of this custom gantry also resulted in reduced ground stabilization and fewer trucks because each carried clean, completed bridge segments.

While this project offers many benefits to Sound Transit and community members in and around Seattle, the project team was met with the unique challenge of navigating around the "spaghetti bowl" that is Seattle-Tacoma International Airport's intertwining roadways. To mitigate this, the team suggested using a long-span, balanced-cantilever structures throughout this area instead of the typical span arrangement suggested in pre-bid documents. The solution eliminated the need for four piers and several straddle bents, which would have severely restricted future development in the area. The use of long-span, balanced-cantilever construction in this area also eliminated the need for additional construction phases, multiple detours, and accommodated the airport's plans for future expansion. The construction of the bridge is complete, and the project teams are working to finish the station and systems work. The new system is estimated to be fully functional as early as spring 2016.

Not only will these unique transportation solutions provide immediate benefits to the airport, but it is the nature of post-tensioned, precast, segmental bridges to provide long-term durability, possibly exceeding the 100-year design-life requirement.

A First Time for Everything

The South 200th Link Extension is a turnkey project for Sound Transit because nearly all aspects of the design-build project, from design to service operations, were delivered in one contract. "I have greatly appreciated the team's willingness to share lessons learned and collaborate," said Miles Haupt, Sound Transit's project director for South Link. "This project was a team effort, and we worked together to bring a more accessible light rail to the Seattle-Tacoma communities."

Heather Yount is a communications coordinator for PCL Civil Constructors Inc. in Denver, Colo., and Bryant Helvey is a superintendent for PCL Civil Constructors Inc. in Seattle, Wash.

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

PROJECT

US 17-92 Interchange at SR 436

From congestion to concrete innovation

by T. J. Lallathin Jr., DRMP Inc.

The team's cooperative attitude allowed the project to meet and exceed the projected project schedule. The project is anticipated to finish 30 days ahead of schedule. Photo: Jim Uhing Photography.

Revamping one of the most congested intersections in the state of Florida was no small feat. With over 100,000 motorists traveling daily through the US 17-92/SR 436 intersection, located in Casselberry, Fla., designing and constructing a grade-crossing structure to alleviate traffic presented multiple challenges. These challenges included accommodating the Florida Department of Transportation (FDOT) District Five's budget, an accelerated schedule, and the unprecedented delivery and installation of the longest single-piece prestressed concrete beams in not just Florida, but the United States.

In the end, the design-build team will improve upon the bridge's construction schedule with minimal impacts on traffic—ultimately saving taxpayers millions of dollars and improving the mobility and safety of the intersection.

Project Background

Just 13 miles north of Orlando, Fla., the US 17-92/SR 436 intersection accommodates a heavy volume of commuter traffic and provides a major pipeline to motorists coming from Interstate 4 (I-4). Prior to construction, the junction of the two six-lane arterials was subject to heavy congestion and major delays, with motorists' wait time clocking in at 4 to 5 minutes. The solution was the construction of a bridge to carry US 17-92 over SR 436. The bridge is configured in three, simply supported spans with a main span of 209 ft and two approach spans of 124 ft, for a total bridge length of 457 ft. The US 17-92 flyover bridge has drastically decreased motorists' travel time since officially opening in April 2015, with drivers saving an average of 5 to 10 minutes in commute time. Motorists traveling on US 17-92 have realized the greatest improvement since they don't have to stop for the SR 436 cross traffic.

Concrete vs. Steel Superstructure

Originally designed as two separate continuous steel plate girder bridges, our team evaluated other options for the flyover bridge. Maintenance costs for concrete were also more economical compared to steel, which would require routine painting and more rigorous inspection. In addition, shoring towers would be needed to facilitate erection if steel girders were used, which would impede traffic on SR 436. The elimination of the shoring towers reduced traffic impacts and simplified the overall traffic control plan. Other advantages of using concrete beams over steel included improved aesthetics, reduced beam fabrication time, and reduced erection time. The benefits of concrete, coupled with lower upfront material costs, resulted in a total savings of approximately $2 million, not including long-term maintenance costs.

The beams were designed with high-strength concrete (10 ksi) for increased structural capacity, which eliminated a beam line, reducing total beam costs as well as the dead load that must be carried by the

profile

US 17-92 INTERCHANGE AT SR 436 / CASSELBERRY, FLORIDA

BRIDGE DESIGN ENGINEER: DRMP Inc., Orlando, Fla.

PRIME CONTRACTOR: The Lane Construction Corporation, Maitland, Fla.

CONSTRUCTION ENGINEERING & INSPECTION: Metric Engineering, Lake Mary, Fla.

PRECASTER/BEAM DELIVERY: Dura-Stress Inc., Leesburg, Fla.—a PCI-certified producer substructure. Although a shallower beam would have been adequate for the approach spans, the team used the same beam depth for all exterior girders to eliminate the discontinuity in the profile of the structure and to maximize the visual appeal. The approach spans consist of 78-in.-deep Florida I-beams (FIBs) and 96-in.-deep FIBs (exterior), and the main span consists of all 96-in.-deep FIBs. Using the 96-in.-deep FIB, the concrete beams were able to span greater lengths, which decreased cost and the construction schedule and increased maintainability.

Substructure and Foundations

The beams are supported by concrete piers, oriented on a skew, comprised of a tapered cap and three rectangular columns supported by individual footings founded on 18-in. square prestressed concrete piles. While the piers are skewed, the end bents are radial to the centerline of construction resulting in variable beam lengths within the approach spans and constant beam lengths in the main span.

Challenges

The size and weight of the beams posed challenges for every aspect of construction including precasting, delivering, and erecting the beam onto the substructure. Although more efficient and economical, the real test in using concrete beams came in how the team would fabricate, deliver, and erect the 209-ft-long beams. The beams are the longest in Florida and recently confirmed to be the longest single-piece pretensioned beams in the United States.

At 209 ft, the main-span beams are the longest single-piece precast, pretensioned concrete beams in the United States. Photo: The Lane Construction Corporation.

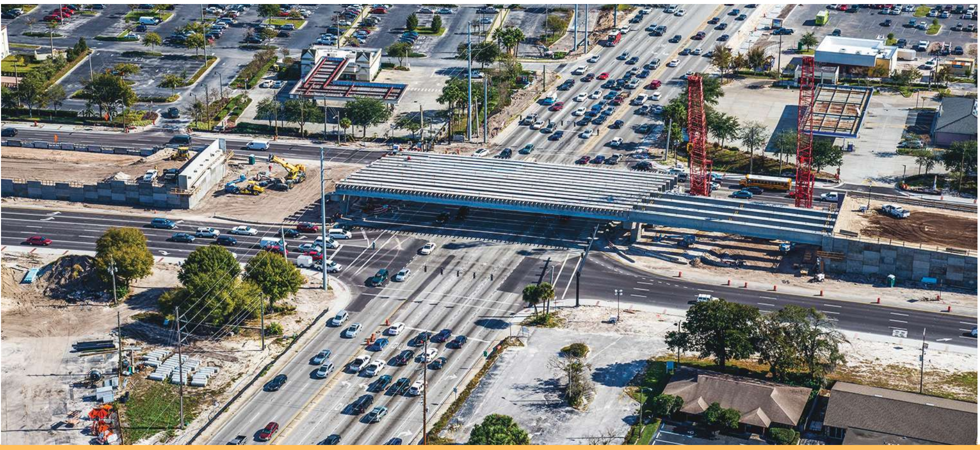
The main span 96-in.-deep FIBs are conventional pretensioned concrete consisting of almost 70 yd^3 of concrete and weighing 267,000 lb. The prestressing consists of seventy-two 0.6-in.-diameter, low-relaxation strands. Additional strands would have caused problems with splitting forces and compression limits. The precaster added additional strands to the top flange of the beam to facilitate stability during transportation. These strands were not originally included in the beam design and were detensioned after erection.

The vertical curve was centered on the bridge. The length of the beams coupled with the steep 5% roadway grade on each end created large build-ups in the center of the span. Build-up values exceeding 8 in. were calculated and had to be accounted for during design. The additional load due to the build-up exceeded 260 lb/ft, which is equivalent to an additional one-third of the total deck load per beam.

The combination of the beam depth, the additional depth of geometric build-up, and the need to support the long span without additional post-tensioning required nonstandard concrete mixture proportions. The increased loads on the main span beam required the use of 10-ksi compressive strength concrete for the beams, which exceeded the current strength allowed by FDOT specifications. Special provisions and approved mixture proportions were required before the FDOT would approve casting the girders with a concrete compressive strength never used before on an FDOT project.

Design and Fabrication

The most significant unforeseen construction challenge was the variation between the predicted camber of the beam and the actual camber. Several factors played into camber differences including how the beam was cast and additional strands added to the beam for handling. These strands were cut at the jobsite before concrete for the deck was placed. The effect of these strands was more significant than expected. Since the strands were fully stressed when the



The project's innovative approach has allowed a major construction effort to have a minimal impact to its dense commercial surrounding. Photo: Aerial Innovations Inc.

FLORIDA DEPARTMENT OF TRANSPORTATION DISTRICT FIVE, OWNER

BRIDGE DESCRIPTION: Three-span simply supported bridge with a 96-in.-deep, 209-ft-long main span and two 124-ft-long approach spans for a total bridge length of 457 ft

STRUCTURAL COMPONENTS: Ten 78-in.-deep Florida I-beams (FIBs) and fifteen 96-in.-deep FIBs; 8½-in.-thick, cast-in-place concrete deck; cast-in-place, 6.5-ft-deep, concrete pier caps; 5 by 7 ft rectangular columns; and footings on precast concrete piles

A potentially complex beam setting was executed in an essentially seamless manner through application of modeling software prior to the actual beam placement. Photo: The Lane Construction Corporation.

Special delivery vehicles were used to transport the beams from the fabrication yard to the project site just over 40 miles away. Beams were delivered at the rate of two per night, resulting in a week-long delivery process. Photo: The Lane Construction Corporation.

concrete was at a lower compressive strength, and cut when the concrete was at a much higher strength, camber growth was reduced significantly.

The only casting bed at the precast facility that could accommodate the 209-ft-long beams was 500 ft in length. To meet the schedule, two beams were cast in the same bed. While this allowed for a faster production rate, one unintended result was varying camber between the two beams. After all tendons were stressed, the first beam was formed and the concrete placed. After the concrete cured, the forms were stripped and placed for the second beam and concrete was placed. Once the second beam's concrete reached the strength required for transfer, the strands were detensioned and both beams were removed from the bed and placed on dunnage. The difference in concrete strengths at the time of strand release caused variations in camber values when measured at the precast yard.

Compounding the issue of camber variation was the construction schedule. A bonus to reduce the project schedule was offered to the contractor after award. This forced the contractor to start erecting beams earlier than the design assumption. The beam age at erection varied from 16 to 58 days. Beams are typically erected at 120 days, which was assumed for design. While all beams had achieved the specified 28-day concrete compressive strength, the large variation in age at erection caused reduced beam cambers and increased variation in cambers.

To fully understand the camber and deflections that were taking place, the beams were surveyed at various stages during construction. At erection before the top transportation strands were cut, the predicted design camber was 4.25 in. The minimum measured camber for all beams at this stage was 2.1 in. Once the top strands were cut the minimum camber value increased to 2.8 in. To better understand the field measured values, a three-dimensional (3-D) finite-element model was created to analyze the various stages of construction relative to the beams. The finite-element model was used to determine deflections for construction staging; the predicted deflections were very similar to field measured deflections.

Delivery

Working closely with a PCI-certified precast concrete supplier, the design-build team addressed the delivery of the thirteen 267,000-lb beams that would need to be fabricated and delivered over 40 miles to the project site. The precaster performed a detailed evaluation of the delivery process, establishing a safe route between their plant and the project site. With two special delivery vehicles capable of supporting 340,000 lb, two beams per night were delivered, resulting in a week-long delivery process. The entire US 17-92/SR 436 intersection was closed and traffic was re-routed during off-peak hours to accommodate the delivery. Due to the length and load of the delivery vehicles, Florida Highway Patrol accompanied them to ensure a safe and uninterrupted delivery.

Erection

The contractor used 3-D modeling software for the development of the beam erection plan. This was of particular importance because of the size of the beams, the relatively small work zone, adjacent traffic, and the proximity of overhead transmission lines. What was fundamentally a difficult beam setting process was completed in a safe and expeditious manner as a result of analyzing the beam setting before it occurred.

Schedule

The schedule for the design and construction of the project was 754 days. The project is ahead of schedule and is projected to beat the schedule by 30 days. This is significant because work is beginning on FDOT's massive, $2 billion, I-4 ultimate project and the client's goal is to open the project to alleviate I-4 traffic. The project is on pace to finish early, aided by the innovative design.

Summary

Through close and extensive coordination between the design-build team, FDOT, the city of Casselberry and other entities, before and after the project award, along with an innovated design approach, central Florida motorists are reaping the benefits. The new US 17-92/SR 436 grade-separation bridge supported by the longest single-piece precast, pretensioned concrete beams in the United States saved millions in taxpayer dollars, has resulted in reduced driving time, and was accomplished with minimal impact to traffic during the process.

T. J. Lallathin Jr. is the design-build manager for DRMP Inc. in Orlando, Fla.

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PROJECT

Replacement of the M-50/I-96 Bridge

MAKING EVERY DAY COUNT

by Bruce L. Campbell, Parsons

The Federal Highway Administration's (FHWA's) current research concludes that 25% of our nation's 600,000+ bridges need repair or replacement on highways that are already heavily congested without the added strain of road closures. In 2009, the FHWA launched the Every Day Counts initiative in cooperation with the American Association of State Highway and Transportation Officials (AASHTO). Goals of this initiative included reducing highway project delivery schedules and providing workable innovations to combat budget challenges, which commonly prevent jurisdictions from tackling much-needed infrastructure projects.

One of the ways that the Every Day Counts initiative is being implemented is through accelerated bridge construction (ABC) methods. ABC technologies are changing the ways departments of transportation (DOTs) across the country do business. Slide-in bridge technology is an ABC method that significantly decreases traffic delays and road closures, improves motorist and worker safety, and reduces project costs.

By advancing twenty-first century solutions, the highway community is ensuring that the nation's roads and bridges are being built better, faster, and smarter. The M-50/I-96 Bridge slide in Lowell Township, Mich., is part of the FHWA's Every Day Counts initiative and is a prime example of the use of innovative ABC technology. According to Roger Safford, an engineer with the Michigan Department of Transportation (MDOT), "This is the type of quality project every engineer wants to be a part of. . .unique, innovative, and extremely effective. Working with such a diverse group of people and watching it unfold the way we intended was very fulfilling. I'm proud that Michigan has raised the bar and set a new standard for bridge replacement."

Project Overview

The $8.1 million replacement of the 1959 concrete-haunched T-beam bridge carrying M-50 over I-96 in Kent County,

Completed replacement of the M-50/I-96 Bridge. Photo: Michigan Department of Transportation.

profile

M-50/I-96 BRIDGE / LOWELL TOWNSHIP, MICHIGAN

BRIDGE DESIGN ENGINEER: Michigan Department of Transportation, Lansing, Mich.

TEMPORARY WORKS/SLIDE ENGINEER: Parsons, Pasadena, Calif.

PRIME CONTRACTOR: Anlaan Corporation, Grand Haven, Mich.

TRAFFIC ENGINEER: HH Engineering Ltd., Detroit, Mich.

SLIDING SUBCONTRACTOR: Mammoet USA South Inc., Rosharon, Tex.

PRECASTER: Stresscon Industries Inc., Shelby Township, Mich.—a PCI-certified producer

M-50 over I-96 traffic on new superstructure in temporary alignment. Photo: Michigan Department of Transportation.

Mich., is part of a complete interchange reconstruction project and represents the state's longest, heaviest, and most rapid bridge lateral slide to date. The project, which is the third lateral slide-in bridge for MDOT, was delivered using a construction manager/general contractor (CM/GC) method. MDOT's own design team produced the final structure design.

An Innovative Solution

The M-50/I-96 interchange serves the community of Lowell, Mich., which has heavy commuter traffic to and from the nearby city of Grand Rapids, Mich. It was evident that the closure of M-50 for bridge replacement would lead to a lengthy detour over rural roads that could not handle the traffic volume. So MDOT, in consultation with the local community, investigated options to reduce mobility impacts of the bridge replacement. This led MDOT to explore ABC options and to eventually select the ABC solution of slide-in bridge technology.

Slide-in bridge technology would substantially mitigate impacts on weekday commuter traffic as well as high traffic volumes on I-96, limiting closure of M-50 to less than five off-peak days over the life of the contract, with no more than two consecutive days of closure at any one time. I-96 closures, other than intermittent closures for beam placement, were not permitted. This is significantly less than the 6 months of traffic detours required for typical bridge construction involving the demolition of an old bridge and construction of a new bridge in its place.

This project is an example of how innovation can be applied to a traditional bridge design. MDOT designed the bridge with spread, 39-in. precast, pretensioned concrete box beams, a cast-in-place concrete deck, cast-in-place concrete barrier railings, on a steel H-pile supported abutment and spread footing pier. This structural system was selected due to its economy, site parameters, and long-term durability. The existing concrete arch bridge had a variable depth of 3 to 6 ft, so the 39-in.-deep box beams were only an incremental difference in the overall structure depth. Cost and fabrication lead-time for structural steel beams were a major consideration. The mass of the concrete box beams was not an issue for the slide-in.

While the ABC technique of slide-in bridge technology resulted in the biggest reduction in lane closure time, a temporary traffic runaround that routed M-50 traffic onto a temporary structure in order to limit traffic impacts was also used. Other innovations, such as partial-width substructure construction and temporary concrete pier caps in lieu of traditional steel caps, further reduced the construction schedule and cost.

Construction

The existing four-span, two-lane bridge was replaced with a wider two-span, five-lane structure. The profile of the new structure was raised to provide adequate under-clearance, which led to reconstruction of the ramps to accommodate the new vertical profile. The new abutments were pile-supported infill, with mechanically stabilized earth (MSE) retaining walls supporting the fill.

With the goal of reducing mobility impacts, the new superstructure was constructed immediately west of the existing bridge from May through July 2014. It was supported on temporary piers and a portion of the new abutments. Temporary roadway approaches and signals were also constructed during this time. Below, I-96 had intermittent 15-minute nighttime closures to set the new beams. The M-50 traffic was then

New superstructure on temporary supports (left) with existing bridge (right). Photo: Parsons.

MICHIGAN DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: The existing four-span structure was replaced with a new bridge that was 33 ft wider to accommodate two additional lanes, including left-hand turn lanes and two full 10-ft shoulders to bring the bridge up to standard.

STRUCTURAL COMPONENTS: Twenty-two (11 each span) 99-ft-long precast prestressed box beams; cast-in-place concrete deck; cast-in-place concrete pier cap, columns, and footing; cast-in-place concrete abutment; and mechanically stabilized earth retaining walls

BRIDGE CONSTRUCTION COST: $8.1 million

AWARDS: Engineering Honorable Conceptor Award from American Council of Engineering Companies (ACEC) diverted to the new structure in its temporary position while the old bridge was demolished.

During the weekend demolition of the existing bridge, M-50 was closed and I-96 traffic was reduced to one lane in each direction and routed up and over the diamond interchange ramps. Then the new bridge permanent location substructure was built along with the remainder of the interchange improvements.

On Friday night, October 17, 2014, M-50 was closed for a second time and I-96 traffic was again reduced to one lane in each direction and routed up and over the diamond interchange ramps. Crews then slid the new M-50 bridge superstructure into place. Three hydraulic jacks were used to laterally move the 4.5 million-pound concrete superstructure 75 ft to its permanent location over I-96. The next morning at 7 a.m., crews began placing the concrete approach slabs, and after curing, completed the temporary railings and pavement markings. By Monday morning at 5 a.m., M-50 was reopened for the morning rush hour.

Design Complexity

A number of design challenges were encountered on this project. It is unusual for a bridge that will eventually be slid into an adjacent permanent location to carry traffic in the temporary alignment because the addition of live traffic loads creates additional design complexity for the temporary support structures and temporary approaches.

The addition of traffic to the temporary substructure, which consisted of a steel pile bent pier with a steel cap, required adding AASHTO design vehicular live loads to the structure. This resulted in a substantial increase in the size of the temporary members; for example, the temporary pier cap beam was a W14 x 426 section. The addition of live loads also requires that all welding for the temporary steel bent be done to AWS D1.5 versus D1.1 and that all welds be fully tested. This adds time and cost to the welding. To avoid some of these impacts, the connections were designed to be bolted.

Prior to start of construction, the CM/GC suggested using a concrete cap in lieu of the steel beam, which reduced costs and shortened the schedule due to the long lead time for the fabrication of a steel beam of this size. Two steel tee shapes were cast into the top of the concrete cap to provide a level and weldable surface for the sliding system channel.

The replacement of the four-span structure with a shorter two-span structure, as well as differences in the vertical grade, led to the design of a complex part-width construction of the approach fill. The design utilized a temporary sheet pile wall, combined with a temporary longitudinal MSE wall, to construct the part-width fill.

The temporary runaround of traffic onto the bridge also required the development of a 25-ft temporary approach span. It was created using 12-in.-deep, non-voided, post-tensioned concrete box beams that sat on the temporary pile bent with concrete caps, and an all-steel bent at the roadway approach. This design facilitated the rapid removal of the slabs prior to the bridge slide.

Construction Challenges

In order to avoid the need to vertically jack the structure to set bearings, the bridge was constructed on the sliding system channel, temporary bearings, and permanent bearings. The temporary and permanent bearings were elastomeric with a polytetrafluoroethylene (PTFE) surface. The sliding shoes, which were a part of the permanent superstructure, had a stainless steel sliding surface. Having the structure rest on the sliding bearings for a long period of time did not cause any issues with breakout forces. However, construction debris and dirt did foul the bearing surfaces and there was not sufficient space between the sliding channel and superstructure to adequately clean the surfaces.

The fouling of the sliding bearings led to some damage and movement of the bearings during the slide. At one point the slide had to be reversed to remove a bearing that became lodged on top of an adjacent bearing after it broke the restraining pintle and slide on top of the adjacent bearing pad. Also during the sliding operation, the middle jack began to experience problems. Since breakout

Temporary pier and span 1 beams in sliding track. Photo: Michigan Department of Transportation.

had already occurred, the contractor was able to complete the move using the jacks positioned on each abutment.

'All bridge replacements should be like this!'

Project Success

Upon project completion, the traveling public in Michigan experienced less traffic congestion and a much safer road. The new structure was now 33 ft wider, accommodating two additional lanes, including left-hand turn lanes and full 10-ft shoulders. Through the use of slide-in bridge technology that prevented prolonged lane closures and long detours, MDOT estimates that motorists saved approximately $3 million in time and travel-related costs. In addition, commercial and industrial activities in the area remained viable with limited disruption of highway access to their locations. One local resident put it, "As a business owner and resident of Lowell, I was worried about this project and the delays it would cause. I attended the public meetings and checked the project website regularly. The animation video spoke volumes about the intent and complexity of this new method. My reservations were unnecessary. All bridge replacements should be like this! What a cool project!"

Bruce L. Campbell is a senior project manager for Parsons in Southfield, Mich.

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Illinois Girder Shapes Offer Design Flexibility

by Kevin Riechers, Illinois Department of Transportation

Earlier this year the Illinois Department of Transportation (IDOT) introduced a series of new precast, prestressed concrete (PPC) girder profiles to supplement their current PPC girder profiles. The goals were to create

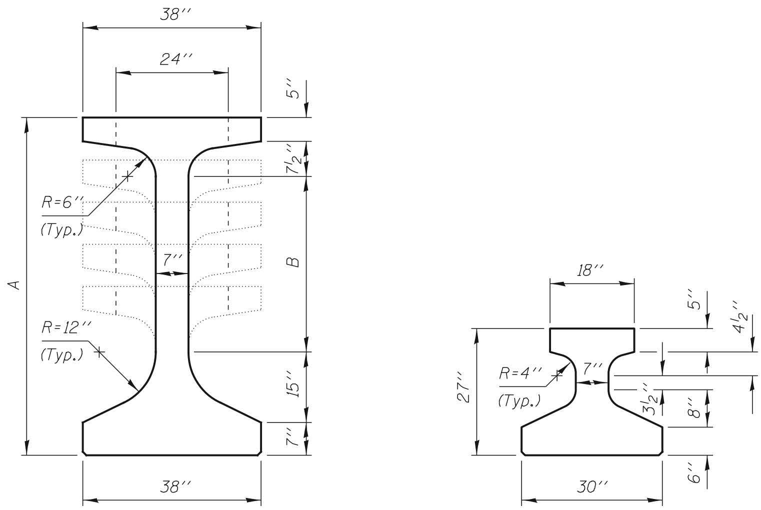
- sections that are capable of spanning further to compete with other materials,
- robust top flanges to better resist damage during future deck replacements,
- improved durability,
- sections with sufficient lateral stiffness to accommodate use for longer spans,
- a variety of functional bridge configurations, and
- sections with future growth potential by utilizing higher concrete strengths.

Before selecting the new beam sections, IDOT reviewed numerous beam configurations and designs from surrounding states and other leading concrete beam states throughout the country. The development process also included close coordination with the Precast/Prestressed Concrete Institute (PCI), concrete researchers, Illinois fabricators, and potential users/owners. All available design options and fabrication techniques were reviewed and revisited to help IDOT achieve its goals.

A total of 11 new beam sections were created. The following are some highlights of their characteristics:

- Six beam depths: 27, 36, 45, 54, 63, and 72 in.
- Narrow, thick top-flanges with two width options
- Large bottom flanges
- Curved flange-to-web transitions
- Concrete compressive strength of 8.5 ksi at 28 days—increased from 7 ksi
- 0.6-in.-diameter, Grade 270 strands
- Epoxy-coated, welded-wire shear reinforcement with standardized spacing

Compared to the new Illinois (IL) shapes, IDOT's current PPC I-beam and bulb-tee beams have smaller cross sections, but the same range in depths is available for both the new and current shapes—36 to 72 in. A new shallower IL-beam with a depth of 27 in. was created to expand the span range for new and replacement structures.



IL36 THRU IL72

IL27

SECTION PROPERTIES

Beam	Area (in^2)	Ix (in^4)	Iy (in^4)	Sb (in^3)	St (in^3)
IL27-1830	457.9	33879	20442	3060.4	2126.7
IL36-2438	728.0	100433	50889	6832.1	4715.1
IL36-3838	805.4	124639	69530	7563.0	6385.1
IL45-2438	791.0	182623	51146	10045.2	6809.2
IL45-3838	868.4	223604	69787	11004.1	9060.1
IL54-2438	854.0	295427	51403	13551.6	9174.7
IL54-3838	931.4	357078	70044	14730.9	11998.5
IL63-2438	917.0	441689	51661	17294.0	11790.9
IL63-3838	994.4	527741	70302	18687.7	15182.4
IL72-2438	980.0	624180	51918	21237.8	14648.6
IL72-3838	1057.4	738236	70559	22855.6	18595.3

Beam nomenclature: ILXX-YYZZ
XX=Beam depth
YY=Top flange width
ZZ=Bottom flange width

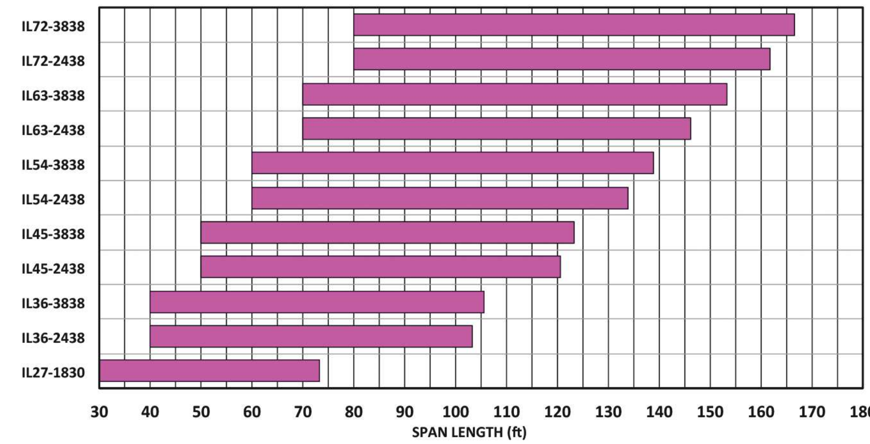
DIMENSIONS

Beam	A (in)	B (in)
IL36	36	1½
IL45	45	10½
IL54	54	19½
IL63	63	28½
IL72	72	37½

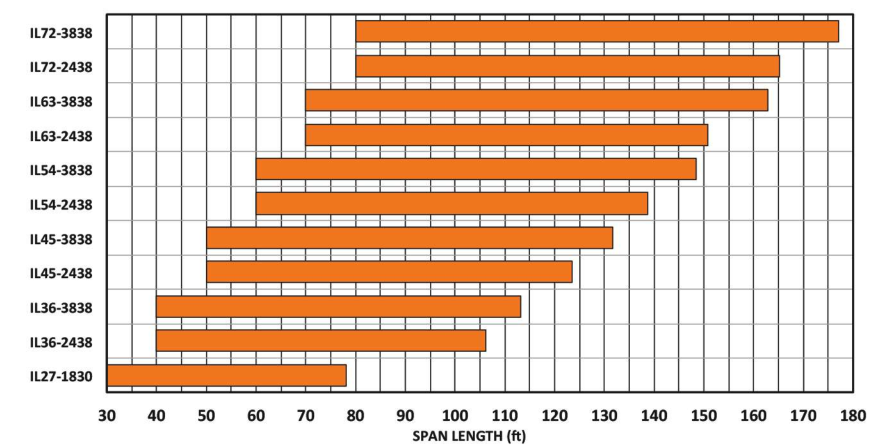
Geometric configurations and section properties for the new Illinois (IL-beam) shapes. All Figures: Illinois Department of Transportation.

Typically, wide and thin top-flange beams provide an efficient prestressed beam design. It's not uncommon to see a top-flange width of 48 in. that's less than 3 in. thick at the outside edges. However, wide and thin top flanges make future deck removal difficult, provide less space for deck drainage options, and offer less flexibility for locating stage lines and concrete closure placements for staged construction.

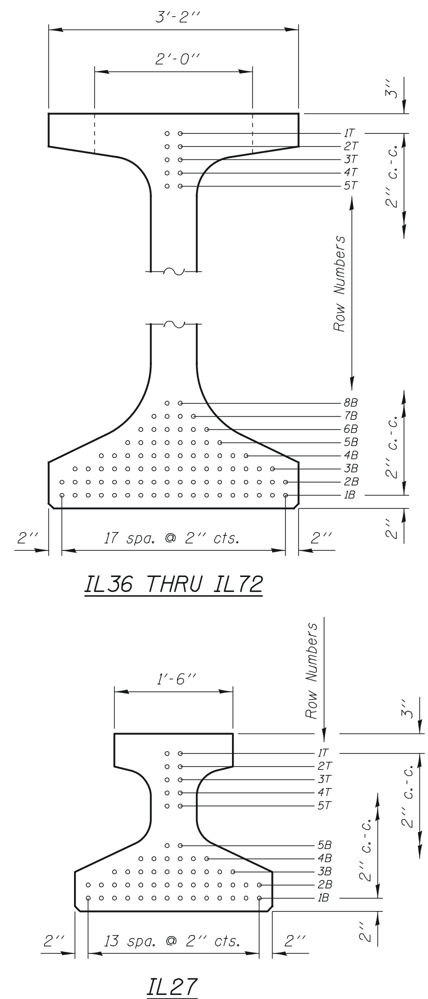
The new IDOT sections have a maximum top-flange width of 38 in., with a minimum thickness of 5 in. The top flange can be reduced to 24 in. with a simple form block-out. These flange configurations help meet IDOT's goals of providing more flexibility and easier removal and replacement of existing decks. This was in line with IDOT's choice of durability and functionality as its top priorities when creating the new sections.



Simple-span ranges for the new Illinois (IL-beam) shapes.



Multi-span ranges for the new Illinois (IL-beam) shapes.



Permissible strand locations in the new Illinois (IL-beam) shapes.

The bottom-flange bulb was sized to accommodate more strands and to improve lateral stability. The 28-day concrete compressive strength of 8.5 ksi with a compressive strength of 7 ksi at transfer enables the use of fifty-eight 0.6-in.-diameter strands in the largest new section, but there is a capacity for 84 strands. This allows room for growth as Illinois becomes more comfortable with greater concrete strengths.

The majority of the sections (IL 36 through IL 72), were created with the same top and bottom flange for fabrication and design efficiency, and the beam depths are in uniform 9-in. increments. The flange-to-web transitions were curved to improve aesthetics and to aid with form removal.

Significant Benefits

The new shapes offer significant benefits for designing with precast concrete girders. The longer spans can eliminate substructure units and move piers out of waterways, creating a more environmentally friendly design. These longer, same-depth sections can also save on overall structure length, embankment work, profile grades, and the need to purchase additional right of way. When shorter spans are needed, the new profiles allow wider beam spacings that can eliminate beam lines, which saves material and construction costs.

IDOT also worked closely with local fabricators and PCI to ensure the new shapes could be transported safely and effectively. The new shapes satisfy the shipping and handling requirements of PCI, and the fabricators will ensure (through evaluation by a structural engineer) that their trucks can satisfy the required roll stiffness for the beam size, length, and delivery route chosen. Additional costs for permits and routing analysis for longer and heavier girders will be included in the bid costs for the girders.

The new shapes provide many improvements over IDOT's current sections, but they are tailored for longer spans and are considerably heavier and therefore may not always be the best economic solution for shorter spans. Situations such as narrow structures with staged construction where beam lines can't be eliminated, or delivery sites with load and geometry restrictions, are typically not suited for the new shapes. For these reasons, the original shapes will remain available for use in unique situations.

Overall, the new girder shapes offer additional robustness, longer service life, more versatility, improved durability during deck replacements, and more functionality to meet the bridge needs in Illinois. IDOT anticipates seeing precast concrete girders being specified in cost-effective designs more often in Illinois thanks to these new girder shapes.

Kevin Riechers is head of the Structural Standards Development Group at the Illinois Department of Transportation in Springfield.

External Tendons with Diabolos—Making Something Out of Nothing

Using diabolos with external post-tensioning increases design efficiencies, streamlines constructability, and improves durability of segmental concrete box-girder bridges

by Jerry Pfuntner, Finley Engineering Group Inc.

Originally introduced in the 1980s, diabolos used in conjunction with external post-tensioning have fallen in and out of favor with departments of transportation over the years. Recent research and a multitude of real-life case studies, however, have even convinced many industry stalwarts that diabolos provide significant benefits over internal post-tensioning or external post-tensioning with standard bent steel pipe deviation saddles, including simplified precasting details, rapid erection procedures, improved long-term durability, and tendon replacement.

Diabolos Defined

Diabolos are uniquely-shaped voids designed and formed into concrete deviator segments in a shape that accommodates the tendon angle change through the deviator. Diabolos allow for a continuous external post-tensioning duct to pass through the deviator without any duct connections. The external tendons bear directly on the concrete void surface within the deviation segment. The shape of the void is similar to the top used in the early twentieth-century game of the same name—hence the origin of the name. Diabolos are used in combination with external post-tensioning in place of the bent steel pipes that have typically been incorporated into concrete deviator segments during casting and offer many advantages in the design and construction of complex post-tensioned segmental concrete box-girder bridges.

The figure to the right illustrates the concept of a diabolo and compares it to a conventional bent steel pipe deviator. The figure is taken from the Federal Highway Administration (FHWA) *Post-Tensioning Tendon Installation and Grouting Manual* (FHWA-NHI-13-026), which addresses the use of diabolos in section 2.3.2.11. The figure also indicates a significant difference between the two details, which is the distribution of stress along the deviated tendon. It has been demonstrated through testing that the more concentrated stresses that occur in a diabolo can be accommodated in post-tensioning systems.

Development of Diabolos

Driven by an endless quest for better results with post-tensioning techniques, Jacques Combault, Finley Engineering Group's technical director, and other experts from around the globe convened an international summit in 2001. The Ghent Seminar was supported jointly by the International Association for Bridge and Structural Engineering (IABSE) and International Federation for Structural Concrete (fib). The experts met to further study some lingering issues about prestressing durability. As a result of the summit, experts determined that external post-tensioning, and the use of diabolos in particular, were deemed to be very effective when applicable. "Furthermore," explains Combault, "the problems that had occurred in the past were relatively easily rectified by providing proper training for designers, contractors, grout suppliers, and installers."

Benefits of Diabolos and External Post-Tensioning

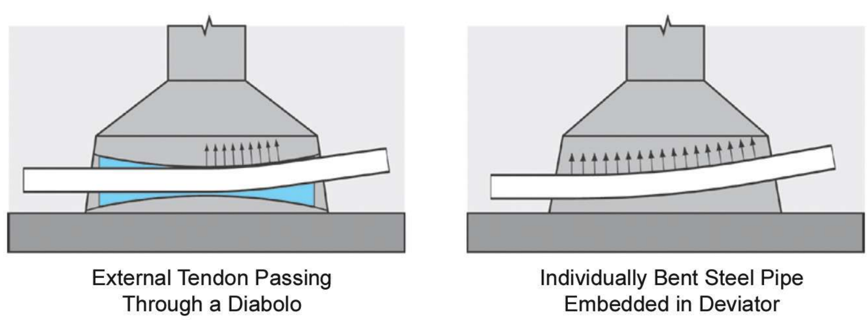
Using diabolos with external continuity post-tensioning tendons increases design efficiencies, streamlines constructability, and improves durability of segmental bridges.

Increased Design Efficiencies

Design and detailing of deviation segments is greatly simplified when diabolos are used for tendon routing. Diabolos can accommodate a wide range of tendon geometry, combined with the bridge horizontal and vertical curvature. This allows for a single deviation segment design for the entire project. The production of one deviation segment design that accommodates all tendon geometry and forces eliminates the effort of individually determining the bent steel pipe fabrication geometry for each deviation point on every tendon. This efficiency in design production also simplifies deviation segment shop drawing production.

Streamlined Constructability

The curved bearing surface of the diabolo void allows for a range of three-dimensional tendon entrance angles to be accommodated. This detail simplifies the external continuity tendon post-tensioning details by eliminating the traditional embedded bent



Schematic details of pressure distribution in a diabolo and bent steel pipe deviator. Drawing: Federal Highway Administration.

Diabolo void forms placed in a precast concrete segment. Photo: Finley Engineering Group Inc.

pipe deviation saddle, and its fabrication, and the associated issues with alignment, bend tolerances, and duct connections. Installation of the external post-tensioning ducts is greatly simplified as the prefabricated continuous duct is routed through the diabolos in the deviation segments, and inserted into each anchorage diaphragm. The duct is then ready for the strands to be installed.

Improved Long-Term Durability

External continuity tendons offer the ability for inspection and repair of nearly the entire length of the tendons during installation and as part of a routine maintenance program for the life of the structure. Because the tendons are grouted to the precast concrete segments only at the anchorage zones when diabolos are used, the removal and replacement of a tendon is a relatively simple operation compared to other post-tensioning systems. Additionally, external tendons ducts located inside the box girders above the bottom slab are protected from the outside environment and potential water infiltration. In addition, the diabolos permit a continuous tendon duct system from anchorage block to anchorage block eliminating problematic connection details between plastic ducts and the bent steel pipes that have typically been used at deviators.

Diabolos permit a continuous tendon duct system from anchorage block to anchorage block.

Deviation segment showing the diabolos with external tendons installed. Photo: Florida Department of Transportation.

Recent Use of Diabolos

Diabolos are becoming more popular with state departments of transportation, designers, and particularly contractors. Their use also fits in with the recent push for replaceability of post-tensioning tendon systems. Recently, as part of an Alternative Technical Concept, the Florida Department of Transportation (FDOT) permitted diabolos to be used on four precast concrete segmental box-girder bridges for the SR 826/836 Interchange design-build project. The acceptance, however, was contingent upon implementing a testing program to determine the adequacy of the polyethylene external ducts when placed and stressed through diabolos.

A testing regimen was developed with the proposed diabolo details and the polyethylene duct supplied to the project. Testing demonstrated that the polyethylene duct more than satisfied the residual thickness requirements at a diabolo after stressing the tendon. This has been successfully implemented in this project, which is currently in service. Based on the success of this project, FDOT now permits the use of diabolos on bridges with external post-tensioning systems.

Summary

The use of external tendons and diabolos can provide simplified precasting details, rapid erection procedures, improved long-term durability, and technical advantages in certain segmental concrete bridge projects. The added benefits of simpler, less costly tendon inspection, maintenance, and replacement over the life of the bridge make an even stronger case for considering the use of external tendons and diabolos for most segmental bridges.

Jerry M. Pfuntner is a principal and senior bridge engineer for Finley Engineering Group Inc. in Tallahassee, Fla.

EDITOR'S NOTE

FHWA Task 5009 Sub-Task 3 on Replaceable External Grouted Post-Tensioning Tendons is currently developing specification language related to diabolos that will be balloted for inclusion in the industry specification PTI/ASBI M50.3-12: Guide Specification for Grouted Post-Tensioning.

Early-Release Cylinder Strengths Predicted by the Maturity Method

Wade S. Bonzon, FIGG Bridge Engineers Inc.

Figure 1. Aerial photo of the southbound main span unit of the Pearl Harbor Memorial Bridge during winter construction conditions. Photo: Connecticut Department of Transportation.

Construction of the recently-completed Pearl Harbor Memorial Bridge in New Haven, Conn., involved placement and curing of concrete elements year-round in a variety of New England weather conditions, in order to meet the challenging construction schedule. Nowhere on the project was the schedule under more pressure than the construction of the main span unit over the Quinnipiac River.

The extradosed cable-stayed, main-span box girder was built in balanced cantilever using post-tensioned concrete segments cast-in-place with self-launching form travelers. With this method, the erection schedule is highly linear and the elapsed times for releasing the form traveler, stressing post-tensioning tendons, and launching the form traveler to the next segment are all dependent on achieving certain minimum concrete compressive strengths in the newly placed segment. A minimum concrete compressive strength of 3.5 ksi was required to be able to release the support of the form traveler and launch it forward to the next casting position. A compressive strength of 4 ksi was needed before stressing the longitudinal and the transverse post-tensioning tendons.

The high-performance concrete used Type III portland cement; ground, granulated blast-furnace slag; and silica fume to achieve a combination of high early compressive strength gain and low permeability. Typically, compressive strengths of 3.5 ksi and greater could be achieved in approximately 16 hours, but the rate of early strength gain was influenced significantly by the curing temperatures. Thus, progression of the segment casting schedule could potentially be negatively affected by environmental conditions during the harsh cold of the New England winters (Fig. 1).

Just as important as protecting the segment during curing was the need to get an accurate compressive strength result from the concrete test cylinders cast and cured with the segment. These early-release cylinders were produced from the last 20 yd^3 of the concrete placement, cured with the segment, and then broken at an on-site lab to determine the in-place concrete strength. On many previous projects, the cylinders had been simply placed under the curing blankets on the top slab of the segment. That method has several potential sources of inaccuracy:

- The cylinders can be inadvertently damaged during or after handling and covering.
- The segment has a complex cross-sectional shape and curing temperatures are not uniform throughout the element. The top slab where the cylinders are located may not be the most critical curing location.
- Cylinders need to be carefully located away from heating sources such as forced air vent hoses.
- The cylinders don't provide any direct data on the curing temperatures at their location or anywhere else in the segment.
- A large number of cylinders need to be produced to determine the point when the minimum compressive strength is achieved.

To reduce these potential inaccuracies and increase efficiency in the early strength gain monitoring process, a quantitative method for monitoring in-place curing temperatures and predicting the resulting test cylinder strengths was adopted for this project.

Based on the maturity method of ASTM C1074,[1] baseline testing was performed that established the relationship between compressive strength and maturity. A test batch of cylinders was cured and broken at regular time intervals. Break results were plotted against the curing temperature history (the maturity index) to establish a predictive relationship specific to the concrete used for this baseline test (Fig. 2). Any subsequent change in constituent materials or their proportions required a new baseline test.[2]

For each segment, several temperature sensors were embedded in the concrete at locations deemed likely to be the most critical for curing temperatures and for structural strength, focusing on locations most sensitive to cold weather conditions and most critical for post-tensioning loads. Generally, this included locations in the thinnest portion of the top slab. Temperatures were also regularly monitored in the bottom slab and in the edge beam near the transverse tendon anchorages.

The project team elected to use a proprietary temperature sensor with excellent long-term durability that had on-board memory for storing recorded data. An additional benefit of this system was the ability to set up a wireless data collection network that transmitted recorded temperatures back to a central computer with automatically updated sensor readings every hour. Thus, the contractor, the owner, inspector personnel had instant access to the raw data via an internet connection and could evaluate the curing system in real time. The on-board memory of the sensors proved useful at times when the wireless communication system had to be turned off or connected to other sensors.

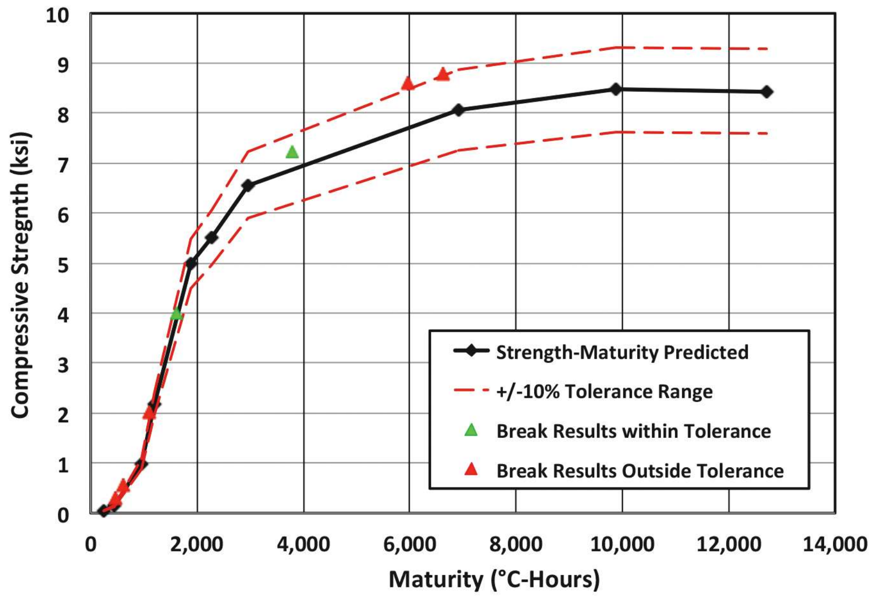


Figure 2. Graph of compressive strength versus maturity index. Figure: FIGG Bridge Engineers Inc.

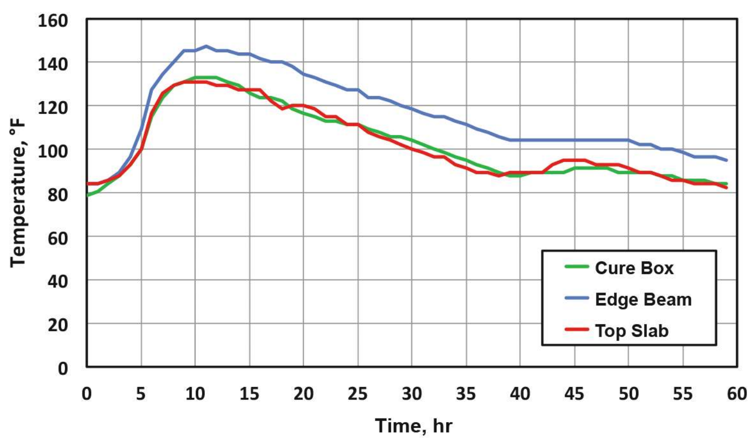


Figure 4. Graph of curing temperatures from segment and cure box cylinder. Figure: FIGG Bridge Engineers Inc.

Monitoring curing temperatures using embedded temperature sensors is not a new idea, and field-curing a set of cylinders to evaluate early-release compressive strength is common. The key piece of hardware that tied these two concepts together and allowed consistent application of the maturity method was a thermostatically controlled curing box that housed the early-release cylinders and one cylinder cast with an embedded temperature sensor.

As shown in the diagram in Fig. 3, the curing box temperature was controlled by one of the sensors embedded in the segment. The selection of the controlling sensor was based on temperatures observed in previous segments. If the selected sensor was not recording the lowest concrete temperature, it could be switched to a cooler sensor as needed. The curing temperature of the early-release cylinders used to calculate the maturity index was recorded by the sensor embedded in a cylinder cast with the early-release cylinders.

Using this network of sensors and the controllable match-cure box, the project team had a high level of assurance that the early-release cylinders were being cured at temperatures consistent with the lowest observed in-situ temperatures in the segment concrete. This could be easily verified by plotting each sensor's temperature and time stamp on the same graph (Fig. 4). The maturity index for the cylinders was calculated on an ongoing basis and was used to determine the appropriate time to break an early-release cylinder. It should be noted that this system did not eliminate the need to physically test cylinders for compressive strength due to possible variations in the mixture proportions and curing temperature profile compared to the original baseline testing. This temperature monitoring and controlled cylinder curing system provided a number of benefits to the project team:

- The predictable and quantifiable process for determining when to break an early-release cylinder reduced the number of field-cured cylinders that needed to be produced.
- Accurate estimation of the test cylinder strength reduced the number of repetitious cylinder strength tests and shortened unplanned stand-by time of the form traveler crews.
- Multiple sensor locations could be evaluated quickly to ensure that the test cylinders were cured using conservative and appropriate temperatures.
- Temperature data could be acquired remotely and in real time, allowing contractor and owner representatives to evaluate curing data simultaneously and during nonwork hours.

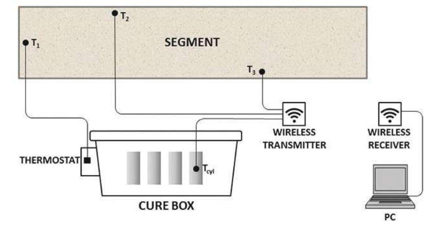


Figure 3. Diagram of sensor and curing box network for curing early release cylinders. Figure: FIGG Bridge Engineers Inc.

Use of the maturity method and the associated temperature recording and curing hardware helped the Pearl Harbor Memorial Bridge project team maintain the segment casting schedule even during cold New England winters. It eliminated the guesswork involved in breaking early-release cylinders and provided a reliable and quantifiable method for monitoring segment curing temperatures.

For more information on the Pearl Harbor Memorial Bridge project, see the Fall 2012 issue of *ASPIRE*.™

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1. ASTM International. 2004. *Standard Practice for Estimating Concrete Strength by the Maturity Method*. ASTM C1074-04, West Conshohocken, PA.
2. National Ready Mixed Concrete Association. 2006. "CIP 39: Maturity Methods to Estimate Concrete Strength." Concrete in Practice, Washington, D.C., www.nrmca.org. <accessed 6 July 2015>.

Wade S. Bonzon is a regional director in the Texas office of FIGG Bridge Engineers Inc. in Dallas.

EDITOR'S NOTE

Lessons learned from this project are included on the website at www.aspirebridge.org

FHWA Strategy to Increase Use of Refined Analysis

by Reggie Holt and Dr. Brian Kozy, Federal Highway Administration

Engineering practitioners of today, with the aid of ever-advancing computer technology, are able to solve engineering problems of great complexity, and produce designs/evaluations that are more refined and more reliable than in the past. However, our nation's governing bridge design specifications and the profession as a whole have not yet fully exploited the capabilities of this new generation of analytical tools. Many bridge engineers and owners appear to favor a general philosophy of keeping analyses as simple as possible to minimize errors or to remain true to the accepted, proven engineering practices. Consequently, they have avoided embracing regular use of refined analysis methods.

In 2009, an international technology scan sponsored by Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and the National Cooperative Highway Research Program (NCHRP) determined that engineers in the United States significantly lagged behind their European counterparts in the use of advanced modeling tools and procedures to design and assess bridges. The scan team recommended increased use of refined analysis for bridge design and evaluation, and encouraged the use of refined analysis to avoid unnecessary posting, rehabilitation, or replacement. Unfortunately, practical implementation of these recommendations has been limited.

What is Refined Analysis?

The generic term "refined analysis" is often used to describe a more-detailed, sophisticated structural modeling approach, which typically involves computerized finite-element analysis (FEA). A significant number of references to refined analysis are made in the *AASHTO LRFD Bridge Design Specifications*, however no formal definition is provided. These references are typically along the lines of "in lieu of a refined analysis, the following can be used," implying that the provided approximate (simplified) analysis procedure is deemed sufficient for most cases, but refined analysis should be considered if more complexity is involved. The AASHTO LRFD specifications also acknowledges and specifies limits of applicability for many approximate procedures indicating that in some cases refined analysis is required.

Therefore, using the AASHTO LRFD specifications as the governing bridge analysis specification, one could define refined analysis as: Any analysis that provides more accurate results or addresses complex structural components/systems or behaviors that fall outside the limits of the AASHTO LRFD specifications' approximate procedures.

Based on the previous definition, analytical procedures that would not be considered refined would include the following:

- Line girder analysis using distribution factors
- Moment magnification procedure for compression elements
- Strut-and-tie models of concrete elements
- Strip method of deck analysis and design
- Cross-sectional frame analysis for box girders
- Equations for effective flange width of composite decks

Conversely, analytical procedures that would be considered refined (Figures 1-3) include the following:

- System modeling that accounts for load distribution to girder lines
- Sectional modeling that accounts for shear lag, local stresses, or distortion
- Models explicitly defining diaphragms/cross frames or the deck as a surface (rather than a grid) in two dimensions
- Models using plastic hinges, such as by pushover analysis

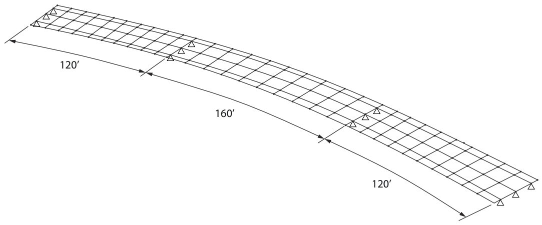

Figure 1. Grillage model. All Figures: Federal Highway Administration.

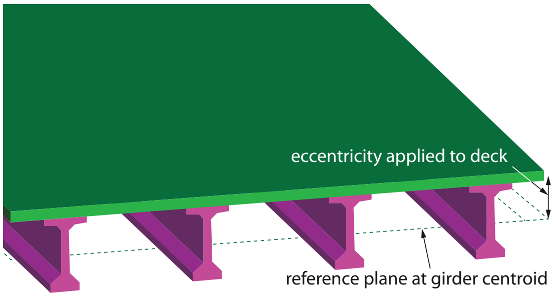

Figure 2. Plate with eccentric beam model.

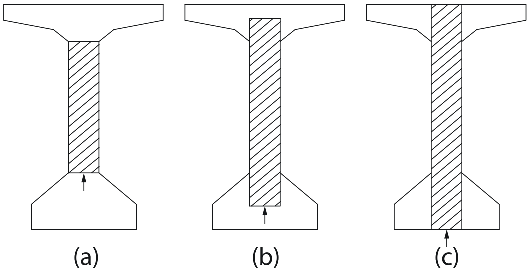

Figure 3. Finite-element analysis web-depth modeling options.

Why Use Refined Analysis?

In some cases refined analysis is *required* to complete the design verification according to the AASHTO LRFD specifications. These are instances for which the code-specified approximate methods do not apply. Furthermore, there are reasons why using a refined analysis might be advantageous, such as capturing behavior not adequately accounted for by approximate methods and/or outside the limits of the AASHTO LRFD specifications.

A properly and efficiently executed refined analysis can provide substantially better information on bridge behavior and performance and allow for more cost-effective and reliable design. Conservatism imbedded in our code-specified approximate methods can add unnecessary cost, which may have serious implications for owner-agencies with limited budgets. At the same time, the AASHTO LRFD specifications encourage designers to expend effort on developing and using complex automated calculation tools to execute the necessary code checks rather than performing meaningful structural modeling to better understand behavior. This often hides the controlling factors and hinders the development of new bridge innovations in general.

Practitioners indicate that refined analysis of most bridge structures can be done for only a small premium over conventional, simplified techniques with currently available computer technology. The practice of bridge engineering in the future is expected to take a more holistic approach, where the design, fabrication, construction, inspection, and management will be much more integrated by digital information exchange. Refined analysis is expected to become routine as software vendors develop "translator" and "wizard" tools to communicate with database records and generate detailed structural models for engineering analysis.

Refined analysis in bridge engineering has the potential to provide the following benefits in the engineering design and evaluation of our nation's infrastructure:

- Improved structural safety by more rigorous assessment of limit states
- Increased economy by going beyond use of approximate, conservative design formulae
- Increased safety and economy by accurate modeling of system or local behavior
- Improved safety evaluation by full consideration of condition data such as section loss or as-built geometry
- Increased sustainability by more frequently allowing the continuing use of existing infrastructure
- Accelerated innovation development as industry gains a deeper understanding of bridge behavior

A New Manual

FHWA has concluded that there is insufficient technical guidance in the literature on the proper application of refined analytical techniques for bridge engineering. A credible resource is needed that will establish and demonstrate the requirements for proper application and define an industry standard of care. In an effort to address this gap, FHWA is working on a manual that will provide standard modeling procedures and benchmark solutions to guide engineers and provide a consistent set of results for verification.

This manual will fill a very important void and provide the necessary guidance for engineers and owners to consider and apply refined analysis. Volume 1 (covering general procedures) is available now, and Volume 2 (covering material-specific details) is scheduled for completion in late 2016. A preliminary version of this manual is available on line at www.fhwa.dot.gov/bridge/refined_analysis.pdf.

Going Forward

The AASHTO LRFD specifications clearly recognizes refined analysis as a needed tool for our nation's bridge designers. FHWA will continue to promote the expanded use of refined analysis for bridge design and evaluation through development of technical guidance and training and implementation in projects. FHWA is looking forward to working with our nation's bridge design community to advance our current state-of-practice to take advantage of the vast capabilities that refined analysis can provide.

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A PROFESSOR'S PERSPECTIVE

The Structural Engineering World in Which We Live

Metrics, reality, and a few stories

by Dr. Oguzhan Bayrak, University of Texas at Austin

As engineers, we continually seek to measure success by using metrics. Higher education is no exception. For example, in an effort to measure teaching effectiveness, we conduct course instructor surveys. Most certainly, within the confines of the questions asked, those surveys provide useful information during or at the conclusion of a formal course. With that said, we must put those surveys into context and seek for additional metrics, or perhaps others ways, by which we can better align ourselves with the reality of the structural engineering world within which we live. With this article, I would like to share a few of my thoughts on teaching and learning effectiveness and explore the importance of maintaining an effective teaching environment in preparing our students for the real world.

David B. Birrcher, bridge engineer, International Bridge Technologies

"The two most influential elements of the University of Texas program to me have been
- knowledge of code development, both past and current state of the art, and
- practical nature of the laboratory/research projects.

"Code knowledge is a big part of my job. I have really appreciated knowing about the origin of code provisions. It has given me confidence in applying the intent of the code when the language is not clear or when our specific circumstances are not strictly covered or even when applying codes of other countries. When changes are made to the code, it is very important for us to know.

"I work a lot in construction support and construction engineering. We have to make real-time decisions to solve construction problems. University of Texas's research program gave me experience tying reinforcement, building forms, placing concrete, stressing tendons, testing cylinders, and other skills that have helped me solve problems. Obtaining site experience is very valuable as a design engineer and can be difficult to obtain due to limited opportunities. UT's program mirrors the experience that can be gained on site and makes me a better designer as well."

As an instructor, I use a variety of formal and informal techniques to assess student learning. In an effort to structure my views on student learning, I will provide discussions in two different time scales:
- Real-time assessment of student learning
- Long-term assessment of student learning

Real-time assessment of student learning is a key component of knowledge transfer. As I explain concepts, design techniques, or expressions in my class, my number one priority is to stay connected with the class. I cannot accomplish the learning objectives of each lecture if I cannot carry the class with me throughout the classroom discussions. Often, it is possible to read the facial expressions of students. In addition, I use numerous short questions directed to the class to get real-time feedback. When I work on design examples, I engage the classroom in the solutions so that I know that they understand the key concepts. Conversely, by answering those questions and participating in the solution for the design examples, students convince themselves that they are learning what they need to learn in that class period.

Long-term assessment of student learning is just as important as the real-time assessment of student learning. Once students leave the university to face the real world, their education should help them be successful in their chosen careers and establish the foundation upon which they can build to be a leader in their field.

Often we have a reasonably good understanding of real-time assessment of learning because it is much easier for us to gauge teaching effectiveness by looking at the course instructor survey results and the like.

Dr. Robin Tuchscherer, assistant professor, Northern Arizona University

"I had a little more than four years of structural engineering work experience before going to graduate school at the University of Texas. Having professional experience beforehand was extremely helpful in the classroom because it helped me grasp the applicability of what I was learning and how it related to my recent work. This is a powerful way to learn and something I strive to share as much as possible with the students that I now teach. My work in the Ferguson Laboratory provided an additional layer of "real world" experience that helped make engineering concepts more tangible. One thing that I appreciate about the Ferguson Laboratory is that students get to do (almost) everything. This gives context to engineering details and strengthens intuition.

"After graduation, I accumulated an additional three years of structural engineering experience before returning to academia. I was a much different engineer after graduate school than before. The difference was that I had a better understanding of the basis of code provisions. Improved knowledge of the origin of code requirements has allowed me to apply them correctly, sort through the ambiguity, and more effectively assess my work."

Matthew Huizinga, associate, Thornton Tomasetti

"Upon my return to industry after graduate school, and as my career progressed further, the value of my graduate education became clearer. The greatest value was the breadth of technical and nontechnical skills developed, and the holistic approach delivered in coursework.
Coursework at the University of Texas was typically delivered as broader ideas. For example, the earthquake engineering course focused on the theory behind earthquake hazard maps, with less time spent on repetitive design calculations. As my industry design projects began to include site-specific hazard analysis, or time-history analyses, a more theoretical and broad understanding of seismicity, such as the content of my graduate coursework, was important. Similarly, I didn't encounter post-tensioned concrete until later in my career, but had a comfort level with the important design considerations. This is because the prestressed concrete course emphasized a unified understanding of concrete behavior; this was much more valuable than routine training with any specific code, design method, or software package. My graduate education granted me a large degree of flexibility in pursuing challenging professional work.

"Beyond developing practical design expertise, research participation also developed other skills: a greater understanding of proper technical writing, implementation of the scientific method, critical problem solving abilities, and practical hands-on experience. As I advanced within my company, these nonanalytical skills have become increasingly important."

Long-term assessment is much harder to assess through simple metrics. It requires following up with our students and asking what helped them transition into the real world and what must be emphasized in our program. In an effort to do just that, I contacted three former students and asked them to summarize their experience transitioning to the so-called "real world." Responses that I received from three graduates of our structural engineering program are included in the article sidebars.

The approach I took in assessing student learning with a long-term perspective is certainly not scientific nor does it involve a large number of alumni. With that said, the common threads seen in the former-student feedback tell us a story. Coupling the points articulated by the three graduates of our structural engineering program with those I have heard from dozens of other students, I am confident that some aspects of our graduate program have been serving our students well. Those aspects include

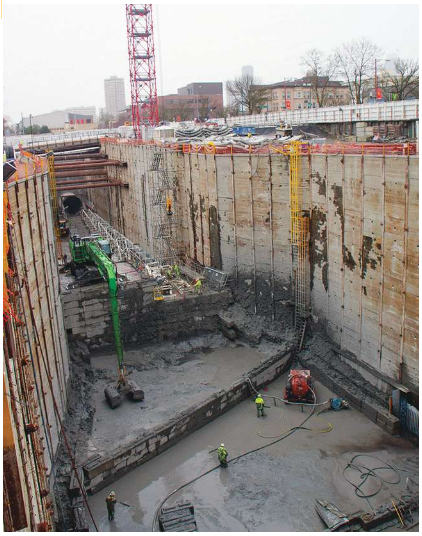
- emphasis on in-depth understanding of fundamental concepts and design codes;
- practical, hands-on experience for undergraduate and graduate students;
- breadth of our structural engineering program; and
- emphasis on technical writing.

With a strong understanding of the fundamentals and a desire to remain practical, a typical student graduating from our program faces the real world with some level of confidence. When this is coupled with a good work ethic and professional attitude, transitioning from graduate school to a typical workplace becomes easier. While I say this, I fully recognize the fact that change is never easy. However, change is what makes us grow and change is a great part of the structural engineering world in which we live.

SOUND TRANSIT FOCUSES ON THE FUTURE

Sound Transit, the Central Puget Sound Regional Transit Authority in the greater Seattle, Wash., area, is expanding its light-rail, commuter-train, and bus services using concrete designs and creative approaches

by Craig A. Shutt



University Link will extend light-rail service from the airport and downtown Seattle to Capitol Hill and the University of Washington. The project includes 3.15 miles of new concrete tunnel track and two underground stations. All Photos: Sound Transit.

The recent completion of the guideway superstructure for Sound Transit's South 200th Link Extension of their light-rail project (see page 16) represents only the latest milestone in a series of expansion projects for the agency. Those programs involve a variety of construction projects, including the use of a precast concrete "floating slab" design in the University Link Extension that will open in the first quarter of 2016. As with all of the agency's projects, the new structures will feature concrete designs.

"Finishing the guideway moves us one step closer to extending light rail to the Angle Lake community," said Dow Constantine, Sound Transit board chair and King County executive, after the contractor completed hoisting the final 35-ton concrete segment in mid-July.

The South 200th Link Extension adds to the agency's 15 miles of dual-operating track and includes 6 miles of dual-track elevated guideways, which use concrete designs. "All of our elevated guideways are concrete," says Kimberly M. Reason, public information officer for communications and external affairs. "Sound Transit prefers concrete to steel because of lower maintenance costs and less concern about stray currents and corrosion issues."

Federal Funding Aids Work

Much of the funding for these programs comes from competitive federal grant monies along with locally generated tax revenues. "Sound Transit values its federal partnerships, which are the key to funding its capital projects," Reason says. Funding for recent projects has included:

- $74.99 million in the proposed 2016 federal budget to expand the Tacoma Link line.
- $10 million in Transportation Investment Generating Economic Recovery (TIGER) funding awarded in 2013 for the Tacoma Trestle project.
- $10 million in TIGER funding awarded in 2011 for the South 200th Link Extension light-rail project.

The University Link project is 6 to 9 months ahead of schedule and $150 million under budget. The key challenge was constructing the 23 cross passages between tunnels, which went smoothly.

The University Link Extension features a 440-ft-long stretch of vibration-damping rails under Capitol Hill that "float," or rest, on 7.5-in.-thick elastomeric isolation bearing pads.

- $813 million in a Full Funding Grant Agreement in 2009 from the Federal Transit Administration for the University Link Extension project now under construction.

The public has responded to this expansion of infrastructure. In April, Link light rail served nearly 34,000 riders on an average weekday, while Sounder commuter rail served an average of 13,600 riders per weekday. More than 64,000 riders used ST Express buses each weekday. Ridership will continue to grow as more people continue to move to the area, Reason notes. By 2040, population in the central Puget Sound area is expected to rise 40%, adding 1 million residents.

Sound Transit's concrete projects are designed to handle that influx, with innovative structures created. The University Link Extension, for instance, includes a 440-ft-long stretch of vibration-damping rails under Capitol Hill that "float," or rest, on 7.5-in.-thick elastomeric isolation bearing pads. The vibration-damping rails are testing how a twin 3675-ft-long stretch of "floating" rail for the Northgate Link tunnels will function when trains pass under the University of Washington's Physics Department.

Sound Transit also is constructing light-rail extensions for the cities of Seattle and Tacoma, and the Northgate area, with planning underway for extensions to Kent-Des Moines, Lynnwood, and Bellevue. In July, the legislature granted Sound Transit $15 billion in new funding authority to place another ballot measure before voters in November. Known as ST3, it will fund mass-transit expansions to Everett, Redmond, and Tacoma, among other areas. Clearly, Sound Transit's work has just begun.

Willow Street Bridge

by Matt Hopkinson, Massachusetts Department of Transportation

The completed Willow Street Bridge. Photo: John Phelan.

Installation of the precast concrete arches for the Willow Street Bridge. Photo: Matt Hopkinson.

Originally built in 1847, the Willow Street Bridge is a two-lane structure that spans over the Charles River between Needham and Dover in Massachusetts. The bridge is well-traveled—by cars and bikes alike—and contributes to the area's historic charm. Reconstructed in 1930, the superstructure consisted of a single-span, reinforced-concrete spandrel arch supporting earthen fill and a bituminous concrete wearing surface. The foundation was composed of two concrete abutments with U-shaped wingwalls, with a stone façade, including some original materials considered historic.

By the early 2000s, the condition of the bridge had deteriorated enough to warrant replacement of some of the bridge's components. The replacement structure was initially scheduled to be a reinforced cast-in-place concrete arch and wingwalls. However, after assessing the impact this approach would have on local traffic, as well as environmental concerns for construction in water, the project team decided on an accelerated bridge construction (ABC) approach using a precast concrete arch and wingwalls.

Because the historic stone façade was so important to the community character, the precast concrete structure was designed to closely match the appearance and geometry of the original bridge above the waterline but differed somewhat beneath. The design incorporated as much of the existing stone facing as possible, which was mapped by the contractor before demolition so that it could be replicated during construction. In addition, a crash-rated CP-PL2 barrier, with the addition of stone facing from the existing arch and with new stone facing similar to the existing one as needed, was placed on the bridge and extended out on all four quadrants.

The original, single-span, reinforced concrete spandrel arch Willow Street Bridge. Photo: Matt Hopkinson.

Ten precast concrete arch sections were used to make the 55 ft 6 in. span with a 9 ft 2½ in. rise. The width of the sections varied between 3 and 4 ft. Each arch section was a single piece and was delivered on a special extendable trailer. The arch sections were grouted at the ends and longitudinal joints were sealed with a bituminous layer. Backfill was placed in 8 in. lifts, with a maximum of 2 ft differential fill between each end of the span.

Each piece had four lift points, the lowermost being used later for weep holes. Each of two cables were attached at two of the points, forming two inverted vees, with pulleys at the top to equalize the load. The two exterior units had a portion of the spandrel wall cast into them. When lifted by the crane, these two units were found to be top heavy and could not be lifted into their proper position. Some quick calculations indicated that the unit could be lifted by the two uppermost lift points without undue stress and the erection proceeded on schedule.

Construction began in late 2010 and was completed in the fall of 2012. The bridge was closed entirely, so crews completed the new construction on site, moving the precast concrete arch sections and spandrels. Using the precast concrete structure resulted in a much faster construction time.

Matt Hopkinson is with the Highway Division of the Massachusetts Department of Transportation in Boston.

Marble Falls Bridge

by Aaron Garza, Texas Department of Transportation

Completed twin segmental box-girder bridges at Marble Falls, Tex. Photo: Archer Western Contractors.

In October 2014, the second of two new twin bridges crossing the Colorado River in Marble Falls, Tex., was opened to traffic. Construction began in April 2013, following demolition of the original steel truss bridge. By applying lessons learned during construction of the first bridge, the contractor and construction engineer sped up production time and completed the second bridge 6 months ahead of schedule.

Designed by the Texas Department of Transportation's Bridge Division, these three-span, variable-depth bridges span 958 ft and provide the city of Marble Falls with a safe, effective, and aesthetically pleasing design. Each bridge carries two travel lanes, wide shoulders, and a 6-ft-wide sidewalk that protects pedestrian traffic. The twin-bridge concept prevents head-on collisions and provides a detour option if one bridge is closed. The bridges were constructed using the balanced-cantilever construction method, via two form travelers (one each side of the pier). The contractor checked elevations and camber and made adjustments as each new concrete segment was placed.

"There was a learning curve associated with the construction of the first bridge, but the key to the project's success was our ability to have the same crew throughout the entire project," says Eric Hiemke, project manager with Archer Western Contractors. "The biggest lesson learned was improving our material quality control. We ordered reinforcement for the segments early, which allowed our team to perform an extensive quality control check on the reinforcement bends and act proactively if there was a problem." Additionally, the contractor learned from the difficulties of drilling shafts on the first bridge and was able to develop means and methods to efficiently remove the underlying dolomite, a hard rock making up most of the bed rock.

Of the 53,000 bridges serving the state of Texas, 22 are segmental structures, and less than 10 are made of cast-in-place concrete. Not only is the design of these bridges unique to the area, but so too is the method of construction. Because of limited access, the need for longer spans, and the desire for a minimal footprint, the cast-in-place concrete segmental design provides a creative solution while maintaining safe and efficient travel along a major north-south highway thoroughfare.

Aaron Garza is with the bridge division of construction and maintenance with the Texas Department of Transportation in Austin, Tex.

EDITOR'S NOTE

For more information on this bridge, see the article in the Spring 2013 issue of ASPIRE.™

Full cantilever at pier 2 of the Marble Falls Bridge. Segment construction is beginning at pier 3. Photo: Aaron Garza.

Resiliency + Sustainability = High Performance

by Emily Lorenz

The transportation-related construction industry has been sustainably minded for some time now. Owners have required that transportation projects, and bridges in particular, take into account the three pillars of sustainability: economy, ecology, and society. In terms of economy, project teams have always been mindful of budgets, and more-commonly consider life-cycle costs rather than just first costs. When avoiding impact to ecology or the environment, projects must commonly work around sensitive habitats and are careful not to disturb waterways or wetlands. Impacts to the traveling public and safety concerns fall into the realm of societal concerns.

While the transportation industry has been at the forefront of sustainable designs for some time, it is important that it transforms to consider the evolution of sustainable, high-performance design to embrace resiliency. This design trend is gaining momentum in the buildings industry, and its principles transfer well to transportation projects also. This article focuses on the importance of resiliency as it relates to sustainable designs, as well as opportunities for the transportation industry to embrace this design strategy.

The Resiliency-Sustainability Connection

Sustainability is often discussed in terms of impact to the environment. And indeed, one reason that we focus on impact to the environment during design is to limit any negative environmental impacts that may exacerbate climate change. Natural disasters significantly affect our economy, our ecology, and our society. And climate change has the potential to increase the frequency, duration, and intensity of natural disasters. Thus, we need resilient structures that can withstand, and continue to function after, natural and man-made disasters.

At all levels of government, decision makers have reached the conclusion that sustainability and resiliency are interconnected. Many have also realized the importance of designing for resiliency so that their communities can continue to function after a major natural disaster. The U.S. Department of Homeland Security (DHS) is an example of a government entity with an increased interest in the resiliency of bridges. "Because bridges are typically more vulnerable than roadways to damage caused by natural and man-made hazards, they are also of interest to the U.S. DHS."[1]

One tool that has emerged to assist communities in assessing their resilience is the *City Resilience Framework*.[2] Developed by Arup with support from the Rockefeller Foundation, the framework assists cities in understanding the factors that contribute to resiliency. This allows cities to "identify critical areas of weakness, and to identify actions and programs to improve the city's resilience."

Still Ahead of the Curve

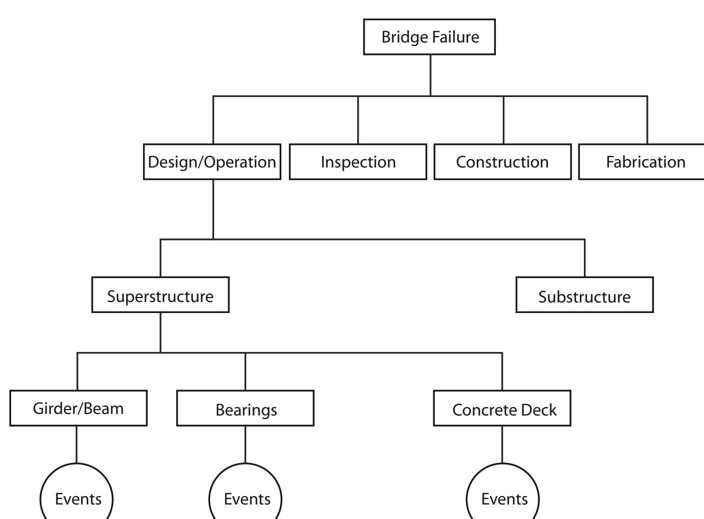
Because highway and transportation agencies have been at the forefront of consideration of sustainable concepts, it is no surprise that the Federal Highway Administration (FHWA) released their *Framework for Improving Resilience of Bridge Design* in 2011.[3] The intent of the framework is to assist designers in

High-performance Structures

According to the *Energy Independence and Security Act* of 2007, the United States government defines a high-performance structure as one that "integrates and optimizes on a life-cycle basis all major high-performance attributes, including:

- energy and water conservation,
- environment,
- safety,
- security,
- durability,
- accessibility,
- cost-benefit,
- productivity,
- sustainability,
- functionality, and
- operational considerations."

Inherent in this definition is that a high-performance structure must consider resiliency. When considering the life-cycle of the structure, one must design to consider major natural or man-made disasters that may impact the structure.



Portion of a fault tree for a typical girder bridge. Diagram: Federal Highway Administration.

achieving more resilient highway bridges.

According to M. Myint Lwin, in his Spring 2012 article in *ASPIRE,*™ "three key factors affect the resilience of highway bridges: ductility, redundancy, and operational importance."[4] When these concepts are applied to the design of a bridge, they allow bridges to better withstand extreme or unexpected forces without collapsing.

While the key is to design a safe, cost-effective bridge while considering these concepts, owners often struggle with balancing these demands with their always-limited resources. A tool to assist in this process is included in the *Framework for Improving Resilience of Bridge Design*. The framework includes a fault-tree methodology that can be used to consider failure analysis during the design process. A portion of a fault tree for a typical girder bridge is included in the figure on the opposite page.

What's Next?

As bridge designers and owners continue to consider economy, ecology, and society in their designs, more long-term planning and design for resilience is the next logical step. First and long-term costs are already computed for most designs, and ecological and societal impacts are largely considered during initial design and construction. Future bridge designs must also consider the long-term impact to the environment and society through increased resilience.

References

1. Homeland Security News Wire. 2012. "Assessing Bridge Resilience." Homeland Security News Wire, Mineola, N.Y.
2. Ove Arup & Partners International Limited. 2014. *City Resilience Framework*. The Rockefeller Foundation, New York, N.Y.
3. Federal Highway Administration (FHWA). 2011. *Framework for Improving Resilience of Bridge Design*. FHWA Publication No. FHWA-IF-11-016, Washington, D.C.
4. Lwin, M. Myint. 2012. "Resilience of Concrete Highway Bridges." *ASPIRE*, Spring, Precast/Prestressed Concrete Institute, Chicago, IL.

CONCRETE CONNECTIONS

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

IN THIS ISSUE

https://www.fhwa.dot.gov/goshrp2/Solutions/All/R19A/Service_Life_Design_for_Bridges
This is a link to the webpage with information and products related to the SHRP2 Service Life Design for Bridges (R19A) project that was mentioned in the Perspective article on page 10. Links to two reports produced by the project follow.

http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2_S2-R19A-RW-1.pdf
This is a link to the SHRP2 R19A project report titled *Bridges for Service Life Beyond 100 Years—Innovative Systems, Subsystems, and Components*.

http://onlinepubs.trb.org/onlinepubs/shrp2/SHRP2_S2-R19A-RW-2.pdf
This is a link to the SHRP2 R19A project report titled *Design Guide for Bridges for Service Life*.

http://parapidbridges.com/
This is a link to the website for the P3 project team delivering PennDOT's Rapid Bridge Replacement Project mentioned in the Focus article on page 6.

https://www.facebook.com/SoundTransit/videos/vb.48453323978/10153491025933979/?type=2&theater
This is a link to a Sound Transit webpage with time lapse video of erecting precast concrete box-girder segments for the South 200th Link Extension bridge described in the Project Profile on page 16. Additional information on the project is also available on related webpages.

http://www.michigan.gov/som/0,4669,7-192-47796-339743--,00.html
This is a link to a Michigan DOT webpage for discussion and a time-lapse video of the lateral slide of the M-50 bridge over I-96 that was described in the Project Profile on page 24. The webpage also provides links to other information on slide-in bridge projects.

https://www.fhwa.dot.gov/construction/sibc/
This is a link to the FHWA website for Slide-in Bridge Construction that was promoted as part of the Every Day Counts initiatives for 2012. This concept was used in the Project Profile on page 24.

http://www.fhwa.dot.gov/bridge/refined_analysis.pdf
This is a link to a preliminary version of Volume 1 of the FHWA manual on refined analysis mentioned in the FHWA article on page 34.

http://www.nrmca.org/aboutconcrete/cips/39p.pdf
This is a link to NRMCA's "CIP 39: Maturity Methods to Estimate Concrete Strength" that is cited as a reference in the Safety and Serviceability article on page 32.

http://www.homelandsecuritynewswire.com/dr20121023-assessing-bridge-resilience
This is a link to an article on the homeland security industry's online news publication Homeland Security News Wire titled "Assessing Bridge Resilience" that is cited as a reference in the sustainability article on page 48.

http://publications.arup.com/Publications/C/City_Resilience_Framework.aspx
This is a link to a webpage from which the three-volume report titled *City Resilience Framework*, which was developed by Ove Arup & Partners International Limited and supported by the Rockefeller Foundation, can be downloaded. The report is cited as a reference in the sustainability article on page 48.

www.fhwa.dot.gov/bridge/pubs/hif11016/hif11016.pdf
This is a link to the FHWA Report FHWA-IF-11-016 titled *Framework for Improving Resilience of Bridge Design* that is cited as a reference in the sustainability article on page 48.

https://www.fhwa.dot.gov/bridge/construction/pubs/hif13026.pdf
This is a link to the FHWA Report FHWA-NHI-13-026 titled *Post-Tensioning Tendon Installation and Grouting Manual* that is mentioned in the Concrete Bridge Technology article on diabolos on page 30.

http://www.dot.state.fl.us/structures/Bulletins/2014/SDB14-06.pdf
This is a link to archived FDOT Structure Design Bulletin 14-06 that specifically allows use of diabolos for external tendons in segmental box-girder bridge as discussed in the Concrete Bridge Technology article on diabolos on page 30.

Bridge Technology

NEW http://library.modot.mo.gov/RDT/reports/TR201414/cmr16-001.pdf
This is a link to a Missouri Department of Transportation report titled *Evaluation of Resistivity Meters for Concrete Quality Assurance* that evaluates a series of concrete mixtures to verify existing relationships between surface resistivity, rapid chloride permeability, chloride ion diffusion, and the AASHTO penetrability classes.

NEW http://www.wsdot.wa.gov/research/reports/fullreports/845.1.pdf
This is a link to a Washington State Department of Transportation report titled *Evaluation of Performance Based Concrete for Bridge Decks* that discusses the early results of changes made to its concrete specification for bridge decks in an effort to reduce early-age restraint cracking.

www.aspirebridge.org
Previous issues of *ASPIRE*™ are available to search and as pdf files, which may be downloaded as a full issue or individual articles. Information is available about free subscriptions, advertising, and sponsoring organizations.

www.nationalconcretebridge.org
The National Concrete Bridge Council (NCBC) website provides information to promote quality in concrete bridge construction as well as links to websites and publications of its members.

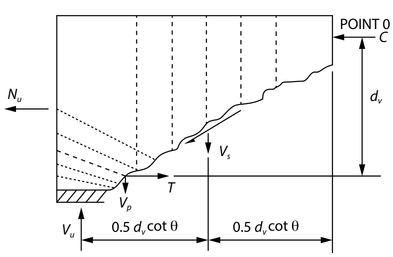
Minimum Longitudinal Reinforcement Revisited

by Dr. Dennis R. Mertz

A reader recently raised the issue of the appropriate application of American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* Equation 5.8.3.5-1 in commercially-available computer software when evaluating shear. This equation, reproduced below, was discussed in this column in the Fall 2012 issue of *ASPIRE.*™ The equation mandates the minimum longitudinal reinforcement based upon the interaction of the force effects at a given section.

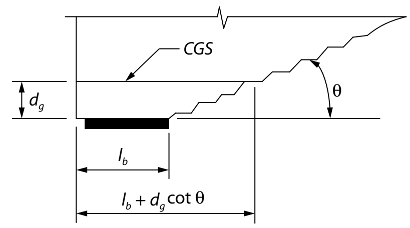
$$A_{ps}f_{ps}+A_sf_y \ge \frac{|M_u|}{d_v\phi_f}+0.5\frac{N_u}{\phi_c}+\left(\left|\frac{V_u}{\phi_v}-V_p\right|-0.5V_s\right)\cot\theta$$

The variables in the equation are familiar to most designers. Their specific definitions are found in AASHTO LRFD specifications article 5.8.3. The interaction of the force effects is illustrated in the free-body diagram, adapted from the AASHTO LRFD specifications, below.



An important aspect of the application of AASHTO LRFD specifications Equation 5.8.3.5-1 near the end of the beam where shear may be critical, which was not previously discussed, is the consideration of transfer and development lengths. In the figure below, the center of gravity of the longitudinal steel, *CGS*, crosses the hypothetical shear crack at a distance equal to distance, l_b, plus the height of the *CGS* from the bottom of the beam, d_g, times the cotangent of the angle of cracking, θ. Then, at this distance, the appropriate steel stress should be computed considering the variation of steel stress within the transfer and development lengths, instead of f_{ps} or f_y as appropriate for prestressed or nonprestressed steel.

Our concern relative to our reader's comment is the force effects: M_u, the factored moment;



N_u, the factored axial force; and V_u, the factored shear force. Are the values of M_u, N_u, and V_u intended to be maximum or concurrent values? As the reader suggests, the equation represents a single point in time. Thus, the force effects should be concurrent values due to a common load condition. The reader's conclusion was also previously addressed in the column of the Winter 2014 issue, wherein the following general conclusion was drawn:

"The various strength limit-state force effects (in other words, the sum of the factored force effects from the governing strength limit-state load combination), M_u, V_u, N_u, and T_u, in the LRFD equations, do not represent the maximums for the section due to varying load conditions. They represent the maximum force effect under consideration along with the other concurrent values for the single governing load condition at each section."

From a design point of view, using the maximum force effects instead of concurrent force effects would be conservative but results in overdesign, perhaps at best a few more stirrups, but an unnecessary overdesign nonetheless.

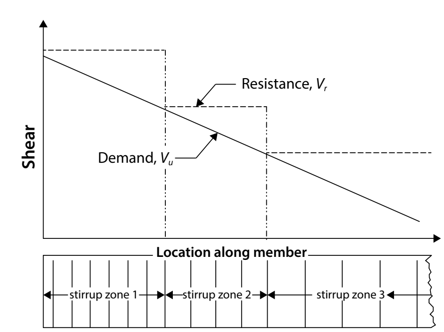
In the case of rating, the evaluator should remember that the Federal Highway Administration *Manual for Bridge Evaluation* states,

"The shear capacity of existing reinforced and prestressed concrete bridge members should be evaluated for permit loads. In-service concrete bridges that show no visible signs of shear distress need not be checked for shear when rating for the design load or legal loads."

In the rare case where a shear rating is required, a lower rating than the intended specified rating will result if maximum force effects are used instead of the more correct concurrent force effects. A reliable bridge could be unnecessarily permit-load restricted. This consequence of using maximum force effects instead of concurrent force effects by rating software was what our reader observed.

Another important consideration in the evaluation of an existing beam such as in rating is the varying spacing of shear reinforcement. In the traditional shear-design approach as shown in the figure below, constant stirrup spacings are chosen to envelope the load or demand curve.

This approach may lead to inaccuracies where several shear stirrup spacings are present within the same zone. Shear failures occur over an inclined plane and a shear crack typically intersects the stirrups within the distance d_v cot θ as shown in the first figure. Each of the stirrups crossing this crack share in resisting the applied shear load and should be included in determining the nominal shear resistance at a section. Using the actual number of stirrups crossing the shear failure plane is the most accurate approach for determining the shear reinforcement resistance, V_s. An example of a Type II AASHTO girder in the *PCI Bridge Design Manual*, 3rd Edition, 2nd Release, illustrates how load rating using the traditional design approach suggests a shear deficiency at a section where the method presented here indicates adequate shear resistance.



Traditional Shear Design

It's important that the user fully understands what the software is doing. Without this understanding, bridges may be overdesigned or underrated. Remember that AASHTO LRFD specifications article 4.4 states, "The Designer shall be responsible for the implementation of computer programs used to facilitate structural analysis and for the interpretation and use of results."