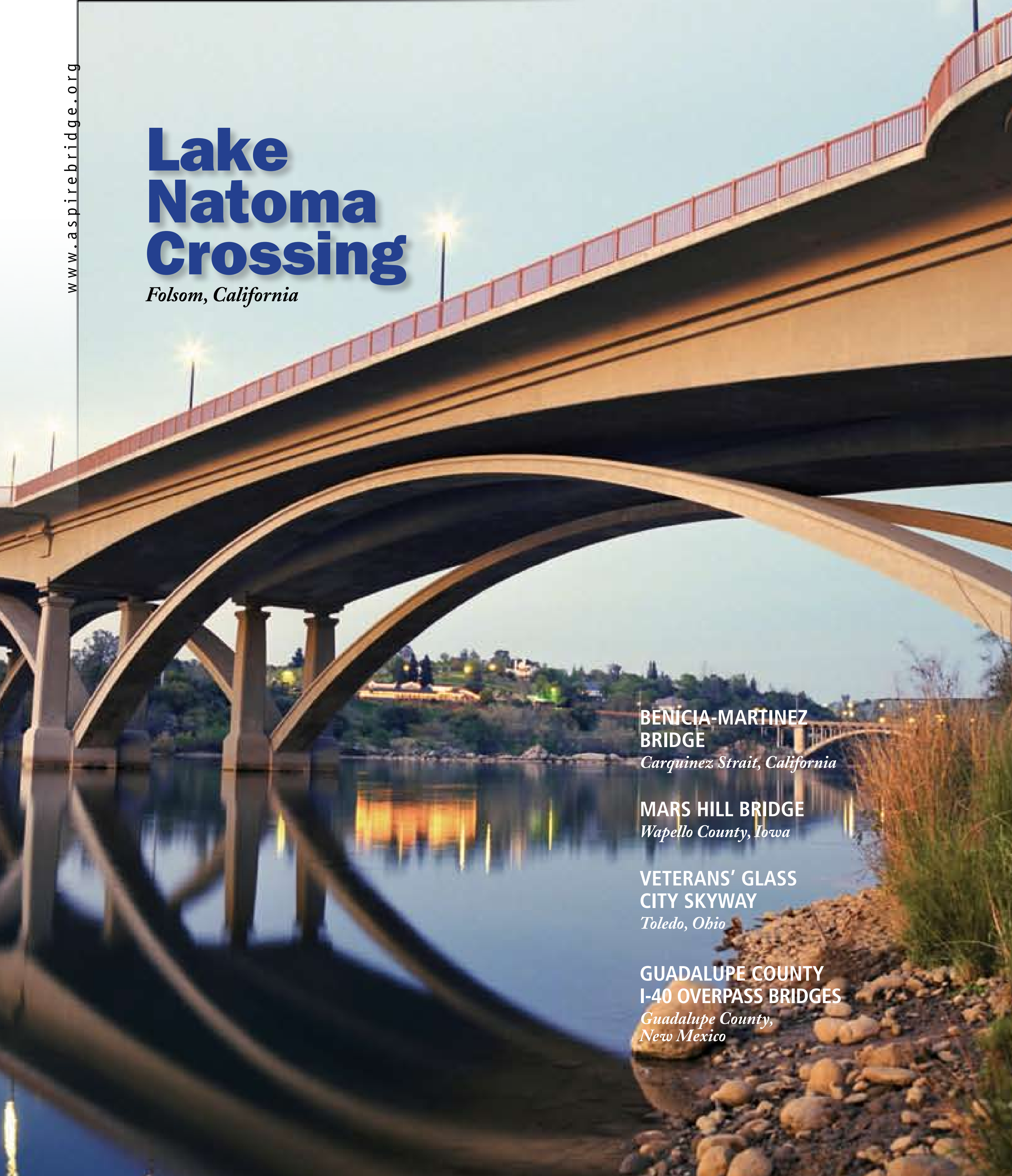
ASPIRE™

THE CONCRETE BRIDGE MAGAZINE

SUMMER 2007

www.aspirebridge.org



Lake Natoma Crossing

Folsom, California

BENICIA-MARTINEZ BRIDGE
Carquinez Strait, California

MARS HILL BRIDGE
Wapello County, Iowa

VETERANS' GLASS CITY SKYWAY
Toledo, Ohio

GUADALUPE COUNTY I-40 OVERPASS BRIDGES
Guadalupe County, New Mexico

Durable Concrete Bridge Solutions

Photo courtesy of Paul Cockrell, HDR.

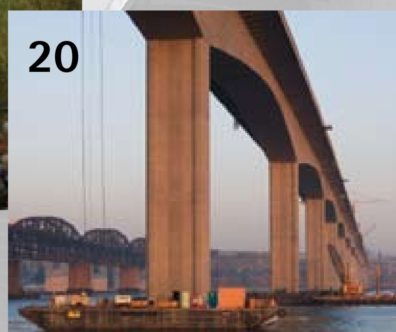


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Photo courtesy of John Huseby for Caltrans.

EDITORIAL

Photo courtesy of Ted Lacey Photography.

ASPIRE™ Magazine . . .

showcasing how you and your peers are meeting challenges and expanding boundaries with concrete bridge technology.

John S. Dick, *Executive Editor*

The theme of this issue of *ASPIRE*™ magazine is durability. While concrete has enjoyed an enviable record in this regard, its past performance is being eclipsed many times over by the concretes and techniques being used routinely today.

An article in this issue by Dr. Celik Ozyildirim (page 15) provides a general overview of many aspects of concrete design and detailing that will result in superior performance. Designers and practitioners will find the article a primer on high performing concrete structures. Another article by M. Myint Lwin (page 42) discusses durability as well and indicates what the Federal Highway Administration (FHWA) is doing to foster durable concrete structures through its many national programs. One of the FHWA's programs is put into practice in the Mars Hill Bridge in Iowa. It uses ultra-high strength concrete that has the potential to create structures that are virtually impervious to the elements.

Through the combination of materials and maintenance technology, design and construction details, and pre- and post-tensioning, concrete bridge designs will be attaining expected design lives of 100, 125 and even 150 years. These goals are being achieved today as shown in the Kansas Haunched Girders article on page 40, as well as most of the other featured bridges.

We'd like to hear about your experiences with concrete bridge building. And, as always, we welcome your comments and suggestions on our magazine. Contact us at *www.aspirebridge.org*. Reader feedback is important to keep this magazine relevant to you, our reader.

A "selected" audience

Just who are our readers? We thought you might like to know that you are part of a select group. We have not taken a random or "shotgun" approach to build our readership. *ASPIRE'S* initial circulation, as outlined below, was carefully selected. The list of our 21,000 readers includes:

- 1600 names from the bridge design offices of state agencies;
- 1100 state engineers including the administrators, the chief engineers, district engineers and engineers of materials, construction, and maintenance;
- 400 federal engineers, principally FHWA HQ and Division offices plus other federal agencies;
- More than 2500 county engineers and commissioners representing 1800 counties;
- 575 municipal engineers and administrators from 440 cities (plus Municipal Planning Organizations);
- 7000 bridge design consultants;
- 2500 contractors;
- 750 professors;
- 50 railroad companies and agencies;
- 200 engineers from toll roads and turnpikes;
- 950 suppliers; and
- 2000 other member engineers of the PCI, ASBI, PCA, PTI, ACAA, ESCSI, NRMCA, SFA, and WRI (our supporting associations).

With each issue, the number of readers is climbing toward our goal of 25,000. Many other professionals have since emailed, called or subscribed online at *www.aspirebridge.org*. Thousands have confirmed their subscription by returning the response card bound in each issue. If you haven't done so, please return yours.

These numbers are particularly important to advertisers. This magazine, like most others, depends on advertising revenue. We are careful with advertising, selecting advertisements that add value to the reader and enhance the quality of the message we strive to deliver.

We believe the quality of *ASPIRE* and its finely targeted audience provides the best opportunity for those companies that need to deliver their message to all stakeholders in the bridge community. Jim Oestmann can assist with inquiries about advertising (call 847-577-8980 or email: joestmann@arlpub.com).

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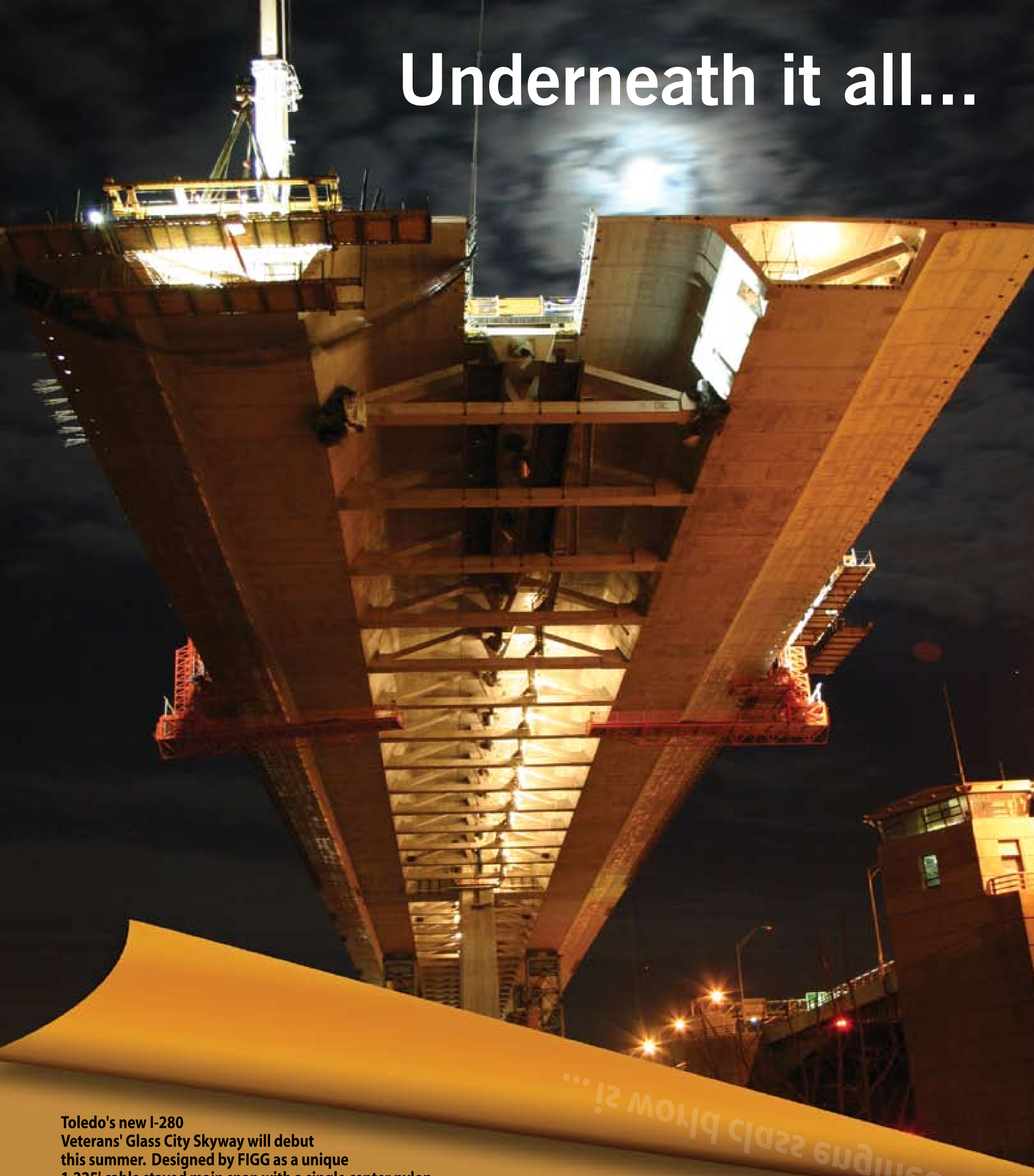
Photo: Paul Cockrell, HDR


Underneath it all...

READER RESPONSE

"The [Aspire] Magazine looks great!"

Joseph Lord
Executive Director
Florida Prestressed Concrete Association
Tampa, Fla.

"I am VERY impressed with your new magazine. John sent me two copies. I am circulating both copies with the request that they be returned."

Robert N. Bruce, Jr.
Tulane University
New Orleans, La.

"I knew our material was in great hands — and the end product is fantastic! You really do have a great crew! Through customers, we've heard really wonderful feedback — thank you."

Cheryl Maze
Director of Lasting Impressions, FIGG
Tallahassee, Fla.

"I would like to request 20 copies of your spring edition Aspire magazine. We would like to pass it out at the Urban Design and Advisory Group of the Columbia River Crossing project. For more information about our project check the website www.columbiarivercrossing.org."

Columbia River Crossing
Vancouver, Wash.

"Congratulations, I just received the inaugural issue of Aspire and I thought that it was great. I commend you and the other industry visionaries for their efforts and cooperation. This magazine will be an excellent . . . tool for the concrete bridge industry as a whole."

Scott Olson
Ulteig Engineers, Inc.
Bismarck, N.D.

"I just read my copy of the inaugural issue of ASPIRE. It looks great. Best wishes for continued success."

Mohamad Hussein
GRL Engineers, Inc.
Orlando, Fla.

I enjoyed reading the second issue of ASPIRE very much. You are off to a great start. I particularly liked the feature on Texas DOT. It gives information that is hard to find elsewhere. Mary Lou's article was excellent. FIGG's article was impressive . . .

Dr. Maher K. Tadros
University of Nebraska
Lincoln, Neb.

"Congratulations on a job well done. The magazine looks great and I am sure it will be well received."

T. Henry Clark, Principal
Ross Bryan Associates, Inc.
Nashville, Tenn.

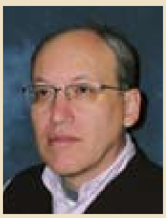
"The new Aspire Concrete Bridge Magazine is a well done magazine and very impressive. It is impressive because it's clear that precast/prestressed concrete bridges are now a major construction method of choice. We have arrived!

Keep up the good work. I'll look forward to future issues of your magazine. It is very informative to read about many of the major PC bridges. I particularly liked the article about FIGG Engineering. Jan, my wife and I [completed] a trip in 2005 to Mississippi via the Natchez Trace Parkway so that we could see, photograph and drive over (twice) the awesome FIGG segmental [arch]."

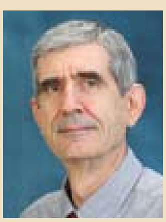
Mac Taylor
McKinney V. Taylor Associates
Richmond, Va.

CONTRIBUTING AUTHORS

M. Myint Lwin is Director of the FHWA Office of Bridge Technology in Washington, D.C. He is responsible for the National Highway Bridge Program direction, policy, and guidance, including bridge technology development, deployment and education, and the National Bridge Inventory and Inspection Standards.



Dr. Dennis R. Mertz is Professor of Civil Engineering at the University of Delaware. Formerly with Modjeski and Masters, Inc. when the *LRFD Specifications* were first written, he has continued to be actively involved in its development.



Dr. H. Celik Ozyildirim is a Principal Research Scientist with the Virginia Transportation Research Council of the Virginia Department of Transportation. He is a Fellow of the American Concrete Institute and an active member of ASTM International and the Transportation Research Board.

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.

Stanley W. Woods worked for the Wisconsin Department of Transportation for 42 years and was the State Bridge Engineer before his retirement.

MANAGING TECHNICAL EDITOR

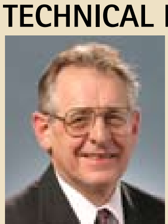


Photo courtesy of Ted Lacey Photography.

Dr. Henry G. Russell is an engineering consultant, who has been involved with the applications of concrete in bridges for over 35 years and has published many papers on the applications of high performance concrete.

CONCRETE CALENDAR 2007/2008

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

June 4-6
International Bridge Conference (IBC) & Exhibition
Includes ASBI Seminar on "Construction Practices for Segmental Concrete Bridges"
Hilton Pittsburgh, Pittsburgh, Pa.

July 8-12
AASHTO Subcommittee on Bridges and Structures Meeting
Also ASBI Executive Committee Meeting, July 8; ASBI Board of Directors Meeting, July 8
ASBI-AASHTO 19th Annual Reception, July 9
Hotel DuPont, Wilmington, Del.

August 1
ASBI Bridge Award of Excellence Competition Entries due

August 6-11
PCI Quality Control & Assurance Personnel Training & Certification Schools
Level I, Level II, and Level III
Embassy Suites, Nashville, Tenn.

August 12-17
AASHTO Subcommittee on Materials Annual Meeting
Mountain Club on Loon Resort, Lincoln, N.H.

September 10-12
American Coal Ash Association Fall Meeting
Crowne Plaza Hotel, Denver, Colo.

September 23-26
Western Bridge Engineers' Seminar & Exhibition
Boise Centre on the Grove, Boise, Idaho

October 14-18
ACI Fall Convention
El Conquistador, Fajardo, P.R.

October 22-24
National Concrete Bridge Conference and PCI Annual Convention & Exhibition
Includes meeting of AASHTO Technical Committee on Concrete Design (T-10)
Hyatt Regency Phoenix/Phoenix Civic Plaza Convention Center, Phoenix, Ariz.

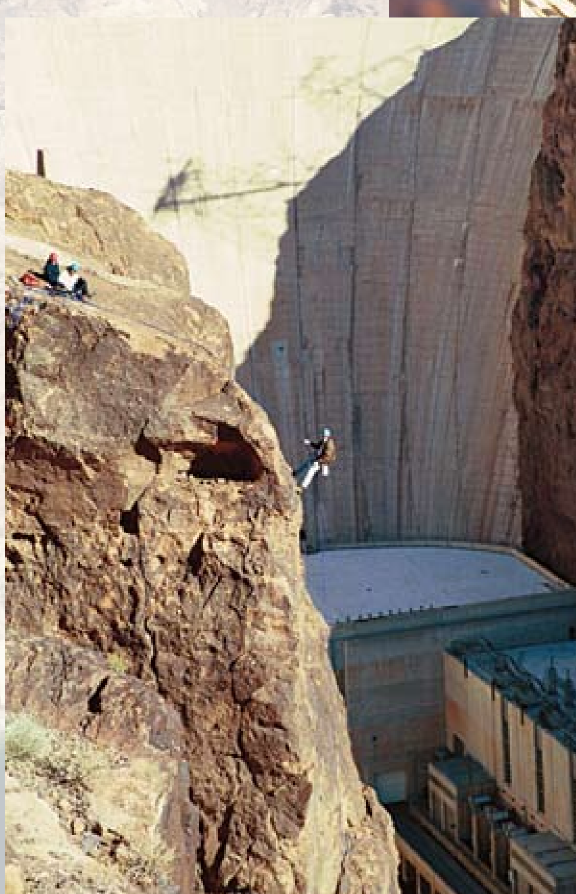
November 4-6
ASBI Annual Convention and Exhibition
Includes ASBI Board of Directors meeting, November 7
Includes meeting, AASHTO Technical Committee on Concrete Design (T-10)
The Orleans Hotel, Las Vegas, Nev.

November 5-7
PCI Quality Control & Assurance Personnel Training & Certification Schools
Level I and Level II
Embassy Suites, Nashville, Tenn.

December 1
ASBI Certified Grouting Technicians and Training Certificate Holders Class of 2002
Deadline for On-line Recertification.

January 13-17, 2008
Transportation Research Board Annual Meeting
Marriott Wardman Park, Omni Shoreham, and Hilton Washington, Washington, D.C.

HDR's impressive growth has expanded its capabilities to better serve clients' needs



The centerpiece for the Hoover Dam Bypass Project is the Colorado River Bridge, a 2190-ft-long concrete arch structure expected to be completed in 2010. The bridge will span the Black Canyon nearly 900 ft above the Colorado River. Photos courtesy of AMEC.

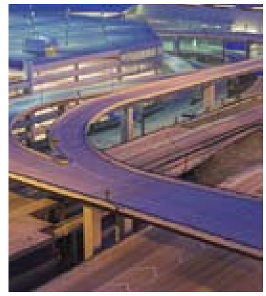
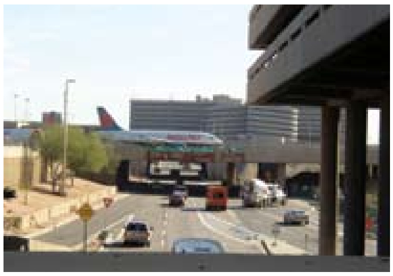
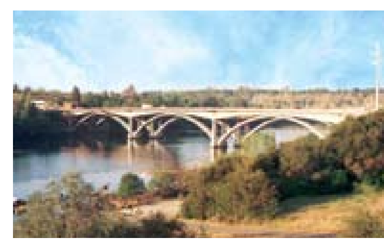


Photo courtesy of Stephen Gould.



Rendering courtesy of T.Y. Lin International.

THE RIGHT BRIDGE FOR THE RIGHT REASONS



By Craig A. Shutt

Rob Turton, Vice President and National Technical Director for Bridges

"Compared to 15 years ago, our expertise has grown substantially. We now can do things we could never have done in the past."

HDR, Inc. has seen phenomenal growth during the past decade, watching its revenues and employees more than quadruple in that time. It has added a wide range of complementary services and offices throughout the country that have expanded the company's markets and expertise. That growth has not made them lose sight of their founders' original philosophy, even as they evaluate new technologies that help expand their capabilities.

"Our motto back in our early years was 'Work Well Done,'" says Rob Turton, Vice President and National Technical Director for Bridges for the Omaha, Nebraska-based company. "That work ethic is part of our heritage and tradition. Today, our unofficial motto is, 'Do the right things for the right reasons.'" This year, the company is celebrating its 90th anniversary by reflecting on where it's been and preparing for the future.

Because of its extensive portfolio and diversity of work, it's difficult to define the HDR style for bridges, Turton says. "There is no specific style, but there is a philosophy. We have to develop solutions that are extremely project specific, and that doesn't allow us to force a particular style. The design has to be honest if it's going to stand the test of time. Our goal is to provide a full spectrum of options, so we can create the right bridge for the right reasons."

Those reasons have become diverse and complicated. "It's a new world compared to even 20 years ago," he says. "We have to make decisions about the structure type, materials, technologies, DOT preferences, public involvement, federal requirements for funding, and many other aspects that might not have been considerations in the past. You can't develop designs in a vacuum today."

Hoover Dam Bypass Bridge Construction. Photos courtesy of Chris Offe/FHWA-CFL.

'. . . The need for good aesthetics has dramatically increased . . .'

Aggressive Expansion Launched

The company's official slogan of One Company, Many Solutions has come to life in recent years as HDR embarked on an aggressive expansion program. The process began in 1996, when a group of 40 managers, led by President/ CEO Richard Bell, bought back the company from its French parent of 13 years, Bouygues. The executives shared ownership with all employees through an Employee Stock Ownership Plan that had been established in the 1970s.

Shortly after this buyback, the company embarked on a strategy of buying small engineering and architecture firms to expand its expertise and national reach. That program expanded dramatically in 2006 with the purchase of nine companies across the country. Past acquisitions have included such firms as HLB Decision Economics in Washington, D.C. and Ottawa, Ontario, Canada, which advises corporations and government agencies.

"We've been experiencing phenomenal growth for a number of years, because we have a cadre of leaders with the vision to go to the next level," says Turton. "It's been interesting for me, as I joined the company in 1997, when we had about 1600 people in 65 offices. Now we have about 6000 people in 140 offices."

That growth has been driven, he notes, by a strong market for their services. "It's important that we've had growing, solid markets with demand. But our expertise and ability to help clients has expanded, as well. Our goal is to be a full-service, extraordinarily diversified organization. Compared to 15 years ago, our expertise has grown substantially. We now can do things we could never have done in the past."

Such broad expertise is required today, he says, because owners' needs have expanded in many ways. "Our DOT clients are dealing with more diversity and more special challenges than ever." When the country's infrastructure was being greatly expanded during the 1950s, he notes, the goal was to build the projects quickly, and aesthetics weren't an issue. The result was a number of cookie-cutter designs. "Today, design drives a lot of projects, and the need for good aesthetics has dramatically increased, especially with the increased public involvement in the process."

Bridge designs are much more focused on being context-sensitive, he notes, but there are additional challenges as well. Speed of construction, and remaining in line with FHWA's "Get in, get out, stay out," philosophy, are paramount, as is maintenance of traffic while work progresses. "That wasn't as big a concern 20 years ago, because the roads weren't as full." Speed of construction and maintaining access are more often than not conflicting goals, requiring a delicate balance that creates new challenges. "Owners today want you to do it all—and they want you to do it well and very quickly."

The AASHTO Load and Resistance Factor Design Specifications adds another layer of challenges, he adds. "It's a more appropriate approach, certainly, but it's more robust and cumbersome. There is still a lot of work to be done to incorporate the specifications into the process."

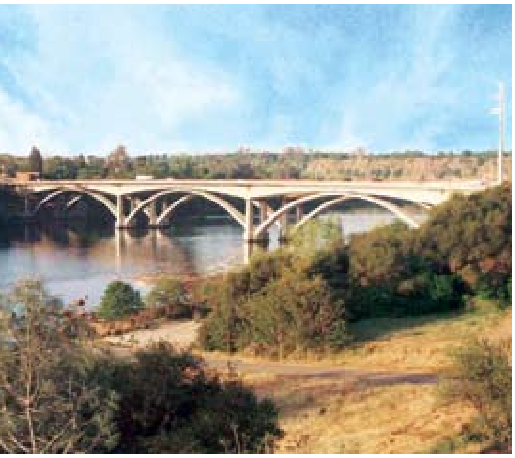
Concrete Aids Designs

Concrete aids with many of these considerations, he acknowledges. "The material we ultimately use varies based on the bridge's needs, as is the selection of a cable-stayed, arch, or girder bridge. We didn't wrestle with as many factors to find an option 30 years ago. We've built bridges from wood, concrete, and steel, when each provided the best solution."

Concrete, he explains, "has absolutely phenomenal features. Number one, it's an extraordinary medium. You can create any shape you want, as if you are baking a cake. It's incredibly flexible in that sense." Precast concrete in particular becomes the material of choice for many projects where maintenance of traffic and speed of construction are both desired.

"Precast concrete plays to that extraordinarily well. And as designs and technology progress, we are better able to use it anywhere, not just in areas with low seismicity." That's important, he adds, because, "We are now identifying earthquake potential in many parts of the country that previously were not considered high-seismic zones."

Regional expertise can be a key factor in guiding the selection process, he says. "Concrete is the material of choice in many parts of the country, and it helps

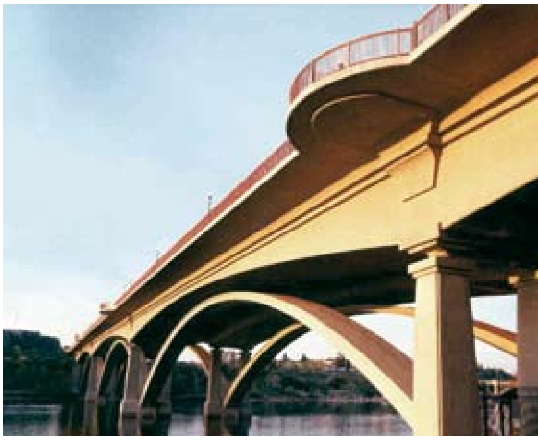


'Owners today want you to do it all—and they want you to do it well and very quickly.'

if you can design to the local industry's experience," he explains. "In some regions, 90 to 95 percent of the bridges are made with concrete, especially if there is a solid precasting industry in the area." In some areas, notably the southwest and parts of the southeast, he says, "the use of steel is limited because of the concrete expertise."

Lightweight Concrete Offers Advantages

Advances in concrete technology have expanded the applications for bridges, he notes. An example can be seen in the company's use of lightweight concrete in the Lake Natoma Crossing in Folsom, California. City officials wanted to add a bridge to span the American River where it widens to form the lake. HDR's design features graceful arches and pleasing architectural details that are visually compatible with the nearby 1917 Rainbow Bridge and the adjacent historic district. Those details include decorative brackets supporting the 4-ft overhangs, with columns and capitals resembling the Rainbow Bridge's architecture.



The Lake Natoma Crossing in Folsom, Calif., consists of a 2300-ft-long concrete box superstructure with three 328-ft-long main spans over the lake. Lightweight concrete helped reduce costs on the project.

‘Someday, I expect we will have a super concrete.’

The 2300-ft-long bridge features a post-tensioned concrete box superstructure consisting of three 328-ft-long main spans over the lake with decorative arches beneath. To minimize cost, the superstructure was constructed with lightweight concrete and supported on seismic isolation bearings placed at the top of the columns and abutments. Foundations consist of large-diameter drilled shafts, penetrating the lake bottom into solid granite for protection against seismic forces and scour effects.

The design was completed ahead of schedule and below budget. “The combined use of lightweight concrete and seismic isolation bearings saved more than $2.5 million in construction costs,” says Turton. “Public acceptance has been high.”

HDR designed renovations for the historic Ford Parkway Bridge, Minn., which spans the Mississippi River to connect Minneapolis and St. Paul. The project involved one of the largest reinforced concrete bridges in the state.

The use of lightweight concrete currently is reserved for specialized cases, he notes, but that could change soon. “The lightweight concrete industry has a challenge in gaining general acceptance, and it’s not there yet, particularly due to cost,” he explains. “But if it provides a way to accomplish a specific solution, the cost can be justified.”

The use of lightweight concrete, as well as self-consolidating concrete, high performance concrete, and other new technologies will continue to expand, he adds. “We’re gaining more superior products every year. Someday, I expect we will have a super concrete with all of these benefits. But there are costs associated with these advantages, and we have to be sure we are using them where the benefits can justify the additional expense. When there are compelling reasons for its use, we definitely consider it.”

HDR’s Early Years

H. H. Henningson, a dynamic and personable engineer, began his career in the early 1900s selling energy products and engineering services to clients in Omaha, Nebraska. With the Midwest quickly emerging from the frontier following World War I, he established the Henningson Engineering Co. in 1917 and began working with the City of Ogallala, Nebraska.

The company grew through the electrification of rural communities in the 1930s and continued its expansion into the 1950s. In the 1930s, Charles Durham joined the firm and married Henningson’s daughter. The two men, along with partner Willard Richardson, changed the firm’s name to Henningson, Durham & Richardson, Inc.

Following Henningson’s death in 1958, Durham spurred the company’s growth, opening offices nationwide, starting with one in Colorado Springs, Colorado. The firm added an architectural department in the mid 1950s, becoming the first company to use airplanes to visit sites around the country.

It greatly expanded its international work during the 1960s, working throughout South America and the Far East. The company was bought by Bouygues S.A. in Paris in 1986, but was bought back by 40 managers in 1996.

Today, the company employs about 6000 people—an increase of more than 4000 in the past decade. Revenues for 2006 were approximately $700 million from 140 offices. The company ranks as the eighth largest nationally for bridge work, 10th largest for transportation and water supply projects, and in the top 20 for mass transit and rail.

HDR designed the new five-span continuous cast-in-place, post-tensioned concrete box-girder underpass carrying aircraft across Sky Harbor Boulevard at the Sky Harbor International Airport in Phoenix. The structure, 400 ft long by 214 ft wide, was designed to accommodate an aircraft load of approximately 2 million pounds.

Renovation Growing Rapidly

The country's deteriorating infrastructure, which has not kept up with maintenance needs, will drive more bridge designs in coming years, as well as the use of concrete with those designs, he says. "There's not enough capacity on our roadways, and maintenance hasn't been kept up since we finished building the interstates. As a result, DOTs are spending more and more time revisiting facilities."

Replacing bridges requires more than swapping out parts, he notes. Because of the bridges' ages—one of the key reasons they're being renovated in the first place—historical concerns can come into play. Seismic retrofits also are driving a lot of work on bridges that otherwise might still be sound. "Some of our infrastructure is obsolete, but some can be upgraded, as long as the landmark features are retained. It takes considerable thought and effort to restore these bridges, but we're seeing more of it."

An example is the Ford Parkway Bridge or the Intercity Bridge, which spans the Mississippi River between St. Paul and Minneapolis, Minnesota. Built in 1927, the 1523-ft-long reinforced concrete arch bridge carries vehicles, bicycles, and pedestrians, but it needed upgrading. The open-spandrel, two-rib, continuous-arch bridge, is listed on the National Register of Historic Places, requiring even more sensitivity in its renovation than most bridges.

The bridge features three main arches, each about 327 ft from pier to pier, flanked by two 158-ft-long arch spans, and six conventionally framed approach spans of varying lengths. One of the largest reinforced concrete bridges in the state, the structure was suffering from spalling and corrosion at and below the expansion joints.

Traffic continued to use one lane in each direction on one half of the bridge during the three-year project. To control stresses and deflections in existing members, the middle 50 percent of an

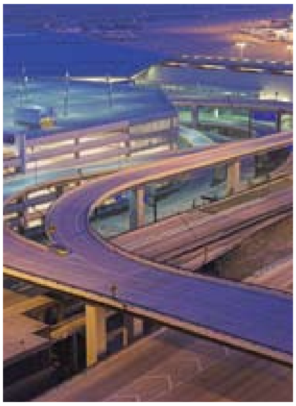
arch was removed and replaced first. After the middle portion of adjacent arches had been replaced the portions over the main pier were replaced. For each portion, the deck and all longitudinal beams except the spandrel beams were removed first, along with floor beams, brackets, spandrel beams, and columns at the existing expansion joints. At other locations, existing columns and floor beams remained to provide rigidity and lateral support.

'The transportation market has expanded far beyond roads and bridges.'

Reconstruction began with casting columns and floor beams at the fully removed locations, followed by spandrel beams that longitudinally connected the new members with the existing structure. To upgrade the bridge, 148 new post-tensioned cantilever brackets extending from the columns and supporting the shoulder and sidewalk were created. Concrete posts at the end of the brackets support the new metal railing, which had to be upgraded from the original concrete design due to new safety requirements.

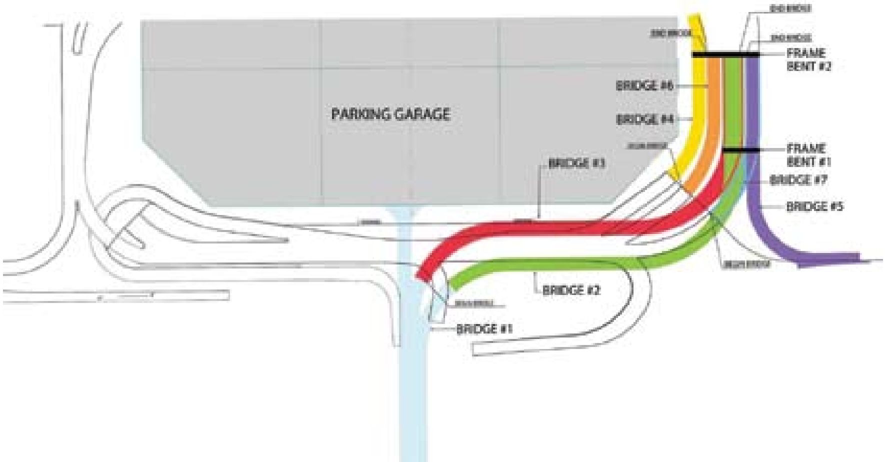
Transportation Field Expands

The company's expansion also has led it into new areas that show how the industry itself has grown, he notes. "The transportation market has expanded far beyond roads and bridges," he says.



Photos courtesy of Stephen Gould.

Construction of a new terminal and infrastructure improvements at the Dallas/Fort Worth Airport includes construction of nine cast-in-place, post-tensioned, concrete box-girder bridges and a precast, prestressed concrete beam bridge.



"We are involved in transit, heavy-rail, commuter, and airport projects. We want to offer a full-spectrum approach."

An example of that work is the major capital-improvement program underway at the Dallas/Fort Worth Airport. The \$2.7-billion program includes \$244 million in infrastructure improvements, \$882 million for a new automated people mover, and \$1.2 billion for a new terminal. HDR's work focuses on designing access roadways, including nine cast-in-place, post-tensioned, concrete box-girder bridges totaling 134,000 ft^2 of bridge deck, as well as a precast, prestressed concrete beam bridge. Also included is 323,000 ft^2 of tri-level cast-in-place concrete beam-and-slab structures linking the new terminal to the existing roadway system.

The firm also has taken on the high-profile Hoover Dam Bypass, which includes the Colorado River Bridge project as its centerpiece. The nearly 2000-ft-long concrete arch bridge, expected to be completed in 2010, will span the Black Canyon and connect the Arizona and Nevada approach highways nearly 900 ft above the river.

The complexities of today's work require more from new engineers entering the field, he says. "A bachelor's degree used to equip you well for this work, but now, you really need a master's degree. You need that extra academic training to be able to hit the ground running."

Hitting the ground running is important at HDR, which continues to expand its offices and staff. "We're excited about the future," he says. "We're looking to continue to grow and add more resources. And barring some type of major catastrophe affecting the economy, I don't see anything that's going to slow us down. The market remains strong, our growing population is demanding more transportation, and there is a definite need for more infrastructure improvements. We're always looking for new expansion opportunities, as we think continued growth fits well with our strategic needs."

For more information on these or other projects, visit www.aspirebridge.org.

Durable Concrete for Bridges

by Dr. H. Celik Ozyildirim

Concrete is a durable material for bridges that can last a long time with minimal maintenance if designed and used correctly for a particular application. Concerns for safety, limited resources, and the desire to reduce lane closures or delays have prompted attention to the durability of concrete bridges worldwide. With new concrete technologies, structures can be built to last a long time. Whereas, bridges were designed previously for a service life of 50 years, this has now been extended to 75 years and more. In other countries, 100 years of service life are planned and structures are designed and built accordingly.

The durability of concrete largely depends on its ability to resist the infiltration of aggressive solutions. Concretes that are protected from the environment and that stay dry can last centuries. There are many good examples of longevity in Roman structures, such as the Pantheon, which was built around 126 A.D. and still remains intact. Today, structural applications use a combination of concrete and reinforcement for efficient load-carrying capacity, and this introduces new challenges in terms of durability. In this composite system of modern times, corrosion of the reinforcement in concrete exposed to water and aggressive solutions has become the most widely experienced distress in concrete structures.

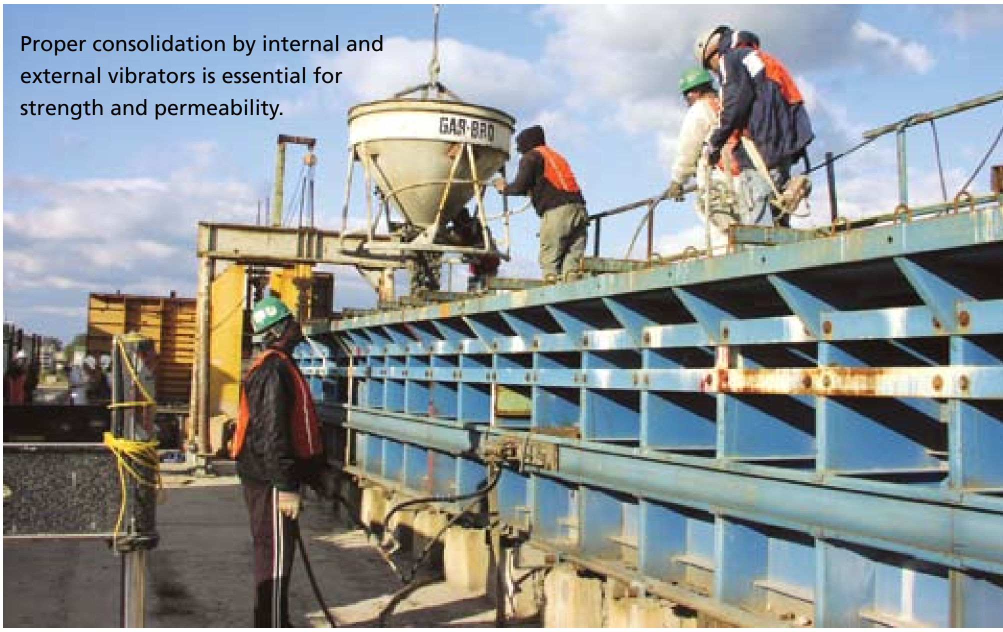
It is not uncommon for poorly executed concrete exposed outdoors to experience reinforcement corrosion, cracking, and spalling within a couple of decades. The same concrete situated indoors and away from the aggressive solutions could have lasted for centuries. Chlorides that reach the steel reinforcement accelerate the corrosion process necessitating costly repairs. Low permeability concretes can resist the penetration of chlorides and thus minimize the damage due to corrosion. In addition, low permeability concrete minimizes other environmental distresses due to cycles of freezing and thawing, alkali-silica reactivity (ASR), and sulfate attack because, in each case, water or aggressive solution entering the concrete is part of the problem. For damage due to cycles of freezing and thawing, another important factor is the proper entrainment of air voids in the concrete. However, low permeability and a proper air-void system do not always ensure durability if the concrete contains excessive cracks that facilitate the intrusion of aggressive solutions. This cracking can be due to many factors related to both environmental effects and structural loads (TR Circular E-C107, 2006).

Building durable bridge structures requires innovation and the use of available resources in an efficient manner. An ideal durable structure needs to have a low permeability concrete with a proper air-void system, no cracks, and not be subject to deleterious chemical reactions. These characteristics are discussed below in relation to design practices, material selection, construction practices, and specifications.

Design Practices

Certain design parameters can assist in achieving durable structures. Good drainage details can minimize ponding and prolonged exposure of bridge components to solutions. Leaking deck joints enable chloride solutions to penetrate onto the substructure elements such as the beam ends, pier caps, and columns causing corrosion. Jointless bridges can minimize such occurrences. Bridge decks supported by more rigid concrete beams exhibit less cracking compared to decks supported by flexible steel beams. Thicker concrete cover provides more resistance to the penetration of solutions to the level of reinforcement. Avoidance of skews on structures can aid in durability as this design feature introduces torsional stresses that lead to diagonal cracking at the corners near the abutments.

The selection of reinforcement is important as well; bars made of tough and intrinsically corrosion-resistant materials can minimize the corrosion potential (Clemena and Virmani, 2004). Bars clad with stainless steel and solid



Proper consolidation by internal and external vibrators is essential for strength and permeability.

stainless steel bars appear to resist corrosion at least 15 times longer than carbon steel bars. Low-carbon, chromium steel bars appear to be a cost-effective option for extending the service life of future concrete bridges. They cost about the same as epoxy-coated reinforcement—another alternative—and are 4.5 times more corrosion resistant than carbon steel bars.

Materials Selection

The use of pozzolans and slag, either alone or in combination, is very effective in reducing the permeability of concrete (Lane and Ozyildirim, 2000). Supplementary cementitious materials (SCM) are readily available, widely used, and extremely helpful in improving the durability of concrete. In addition to reducing the permeability, concrete with SCMs also resists chemical degradation caused by ASR and sulfate attack.

Besides the use of SCMs, a proper water-cementitious materials ratio (w/cm) is effective in achieving low permeability. A lower w/cm leads to lower permeability; however, low w/cm concretes usually have higher autogeneous shrinkage, stiffer consistency, higher cement content, less bleed water, and are more prone to cracking, which negates the concrete impermeability. Therefore, the w/cm should not be too low; a range between 0.40 and 0.45 is commonly used for bridge decks. This, in combination with minimum 28-day design strengths of 4000 psi and the use of pozzolans and slag, provides for low permeability (Ozyildirim, 1998, 1999).

Concrete that gets critically saturated can be damaged by cycles of freezing and thawing unless necessary precautions are taken. Concrete must be properly air entrained, have sound aggregates, and have the maturity to develop sufficient strength for long-lasting service (Mather, 1990). A minimum compressive strength of 4000 psi is often specified for bridge decks. Air entraining admixtures provide small, closely spaced, and uniformly distributed air voids, with a diameter less than 1 mm. The size of the air voids is indicated by the *specific surface*, which is equal to the average surface area divided by the volume of the voids. The average distance water must travel to reach a protective air void in concrete undergoing freezing is indicated by the *spacing factor*. It is generally accepted that a specific surface greater than 24 mm^2/mm^3 (600 in^2/in^3) and a spacing factor less than 0.2 mm (0.008 in) are needed for adequate protection during freezing and thawing (Whiting and Nagi, 1998).

Air void parameters in terms of total air content, spacing factor, and specific surface are affected by many factors including material properties such as water and admixture type and content, and construction practices such as pumping and consolidation (Ozyildirim, 2004). Satisfactory air-void systems indicated by the spacing factor and the specific surface can be established in the development of the mixtures and related to the total air content. Then, field quality control can be achieved through the measurement of the total air content. Too much air in the concrete should be

avoided since it reduces the strength of concrete. In precast, prestressed concrete beams, the stringent air requirements used for bridge decks are not needed unless critical saturation occurs. Since these beams are under the deck and generally have low permeability concrete, they are protected from water intrusion and critical saturation is not expected.

Cracking in bridge structures is mainly attributed to moisture loss and temperature change. Selection of materials also affects the extent of cracking. Mixtures with high water and paste content are prone to shrinkage cracks that occur over a period of time. Use of large-size aggregate and well-graded aggregates reduces the water and paste contents and minimizes shrinkage. In fresh concrete, when the rate of evaporation exceeds the rate of bleeding, plastic shrinkage occurs. The rate of evaporation can be determined using a chart. Means of reducing the evaporation rate can be established. Concrete with low bleed water, stiff consistency, and low w/cm are prone to plastic shrinkage cracking. Prevention of plastic shrinkage cracking depends on prompt and effective curing.

To reduce cracking, shrinkage should be reduced; however, cracking also depends on other factors such as restraint, modulus of elasticity, and creep. Low modulus of elasticity and high creep help to minimize cracking. All these factors should be considered in predicting the

A steady flow of concrete and no large free drops are necessary during pumping.

At least 7 days of curing with wet burlap and plastic sheeting are essential for bridge decks.

cracking potential (TR Circular E-C107, 2006). The use of post-tensioning virtually eliminates the presence of cracks.

Cracking can also occur in cast-in-place bridge decks when temperature management is not used. High temperatures and high temperature differentials can cause cracking. In bridge structures, a maximum temperature differential of 22°F between the beams and the deck is recommended for at least 24 hours after concrete is placed (Babaei and Fouladgar, 1997). To minimize the potential for temperature-related cracking, the amount of portland cement should be minimized, concrete delivery temperature reduced, and pozzolans and slag included.

The desire to reduce cracking due to shrinkage has led to studies with fibers and shrinkage reducing admixtures. Use of structural fibers in large amounts has shown to reduce the severity of cracks

Fog misting can be used to reduce the evaporation rate.

in terms of length and width (Ozyildirim, 2005). In one study, an overlay with a shrinkage-reducing admixture demonstrated that the least shrinkage occurred when this admixture was used (Sprinkel and Ozyildirim, 1998). However, due to prompt and proper curing, none of the overlays in that study exhibited shrinkage cracking making this the more important factor.

Construction Practices

Proper consolidation of concrete is essential to ensure satisfactory strength and permeability. This is usually achieved through the use of internal and external vibrators. For areas that are hard to reach, in areas congested with reinforcement, and when stiff concretes are used, self-consolidating concrete (SCC) may be a solution. SCC can flow into the formwork and encapsulate the reinforcement without any mechanical consolidation. SCC can be very useful for constructing precast, prestressed concrete bulb-tee beams with many strands in the bottom flange and other structural elements with thin walls and congested reinforcement.

Handling of concrete affects the final product. Delay in placement particularly on hot days should be avoided as it can lead to stiffening of the concrete. This may cause tearing of the surface during finishing and produce a poor surface finish. Delivery of the concrete to the forms through pumping can result in loss of slump and air content. Loss of air occurs because bubbles shrink due to

Solutions for Durable Concrete

- Design bridges with close attention to parameters that affect cracking such as joints, flexibility of superstructure, and skews. Use post-tensioning to prevent the occurrence of cracks. Use noncorrosive reinforcement in areas exposed to harsh environments conducive to corrosion.
- Use pozzolans and slag to reduce the concrete permeability, to resist chemical distress, and control heat of hydration.
- Use as much aggregate as possible. This can be achieved by using the largest size aggregate possible and better grading of the aggregates. This will lead to reduced water, cementitious materials, and paste contents.
- Use air entrainment to obtain well-distributed air voids to protect concrete from cycles of freezing and thawing.
- Ensure proper consolidation. Entrapped air voids reduce strength and durability.
- Provide adequate curing. Both moisture and temperature control must be addressed. Immediate attention to moisture loss after screeding and limiting the temperature differences between the core and the surface in mass concrete and between the deck and the beams are needed.
- Specify performance parameters and consider eliminating restrictive prescriptive requirements such as the minimum cement content and maximum water-cementitious materials ratio.

pressure in the pump line, bubbles crush from the impact of the falling concrete, and bubbles expand and dissipate due to the vacuum created when concrete slides in a vertical pipe (Yingling et al. 1992). A steady flow of concrete during pumping should be provided and a large free drop in the pump line eliminated. This generally results in satisfactory freeze-thaw resistance even though the total air content may be lower than specified (Ozyildirim, 2004).

Curing is essential to ensure that the desired properties are achieved. In bridge structures, the cast-in-place deck surfaces require special attention since they have large surface area where loss of moisture is a concern. Also, the temperature in the deck as it relates to the beams is important as explained above. In mass concrete, temperature control to minimize temperature differentials needs special attention. For bridge decks, wet curing involves at least 7 days using wet burlap covered with plastic followed by the immediate application of a curing compound. The wet burlap should be placed immediately after the screeding is completed. If there is a delay, the surface should be fog misted. Concerns that prompt placement of the burlap causes marring of the surface are unfounded. There is no problem with the surface marks from the burlap itself, especially since the transverse grooves cut on hardened concrete or a tined surface make surface marks unnoticeable. However, deep indentations from a footprint or heavy object placed on the burlap may be

Heaters inside plastic enclosures can be used in cold weather.

an issue. In some states, the wet cure is extended to 10 and even to 14 days as in New York.

Additional protection is needed in cold weather conditions. Thermal blankets to retain the heat may not be enough, and external heat may be needed. For example, the deck of the first high-performance concrete structure in Virginia was placed in December, and the cold weather necessitated the use of heaters and a plastic enclosure.

Specifications

Specifications may be either prescriptive or performance based. Most current specifications are of a prescriptive type requiring a recipe of ingredients. They restrict innovation by limiting the use of many possible combinations of materials. In performance specifications, the characteristics of the mixture are specified rather than the mixture itself,

Leaking joints cause concrete deterioration and reinforcement corrosion.

Temperature control is important to prevent thermal cracking.

allowing the producer to innovate in the selection of materials and proportioning of the mixture. The contractor and the user share responsibility; the contractor is responsible for the development of the product and the user in its acceptance. Compensation can be adjusted depending on the quality of the product. For example, the Virginia Department of Transportation has developed an end-result specification, where strength and permeability are specified without any limits on the minimum cementitious materials or maximum w/cms and has been evaluating it on pilot projects.

Large foundations require special attention to temperature control.

Improper consolidation of pier concrete.

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When Lighter is Better

Bay-area bridge features sand-lightweight concrete segments with long spans and a seismically resistant design

In the San Francisco Bay area, two world-class segmental concrete bridges are nearing completion. Last winter's issue of *ASPIRE*™ featured the San Francisco-Oakland Bay Bridge Skyway (Skyway). The second is the 2.5-km (1.5-mile)*-long, 22-span Benicia-Martinez Bridge to be completed this summer. Both are built to withstand earthquakes in high-seismic zones and are considered to be lifeline structures that must remain open to emergency traffic immediately after a major earthquake.

The new Benicia-Martinez Bridge was built to relieve congestion, unlike other toll projects in the Bay Area that were retrofit for seismic needs. When the Benicia-Martinez Bridge is completed, it will carry five lanes of northbound I-680 traffic across the Carquinez Strait between Martinez and Benicia, California. Despite corridor expansions, the existing bridge creates a severe bottleneck for traffic, which the new bridge will relieve.

*The Benicia-Martinez Bridge was designed using SI units. Conversions are included for the benefit of the reader.

Because of their similar construction and time frames, the Skyway and Benicia structures invite comparison. They're both designed as segmental concrete box girder bridges built to withstand substantial earthquakes. The Skyway is renowned for the size of its precast segments, which weigh up to 800 tons apiece, compared to 40 to 60 tons for a more conventional bridge. Benicia-Martinez, though, offers its own unique aspects.

'Lifeline Standards' Used

The California Department of Transportation (Caltrans) required that the Benicia-Martinez Bridge be built to "lifeline standards" because the Green Valley Fault is situated approximately 3 miles east of the bridge. Its location controlled the seismic design.

Although both bridges are constructed primarily using the balanced cantilever method, the Skyway features a precast concrete segmental design and the Benicia-Martinez Bridge is cast-in-place with sand-lightweight concrete. The sand-lightweight concrete uses normal weight sand as fine aggregate and

profile

BENICIA-MARTINEZ BRIDGE / CARQUINEZ STRAIT, CALIFORNIA

ENGINEER: A joint venture of T.Y. Lin International, San Francisco, and CH2M-Hill, Sacramento, Calif. Caltrans designed the northern elevated approach spans.

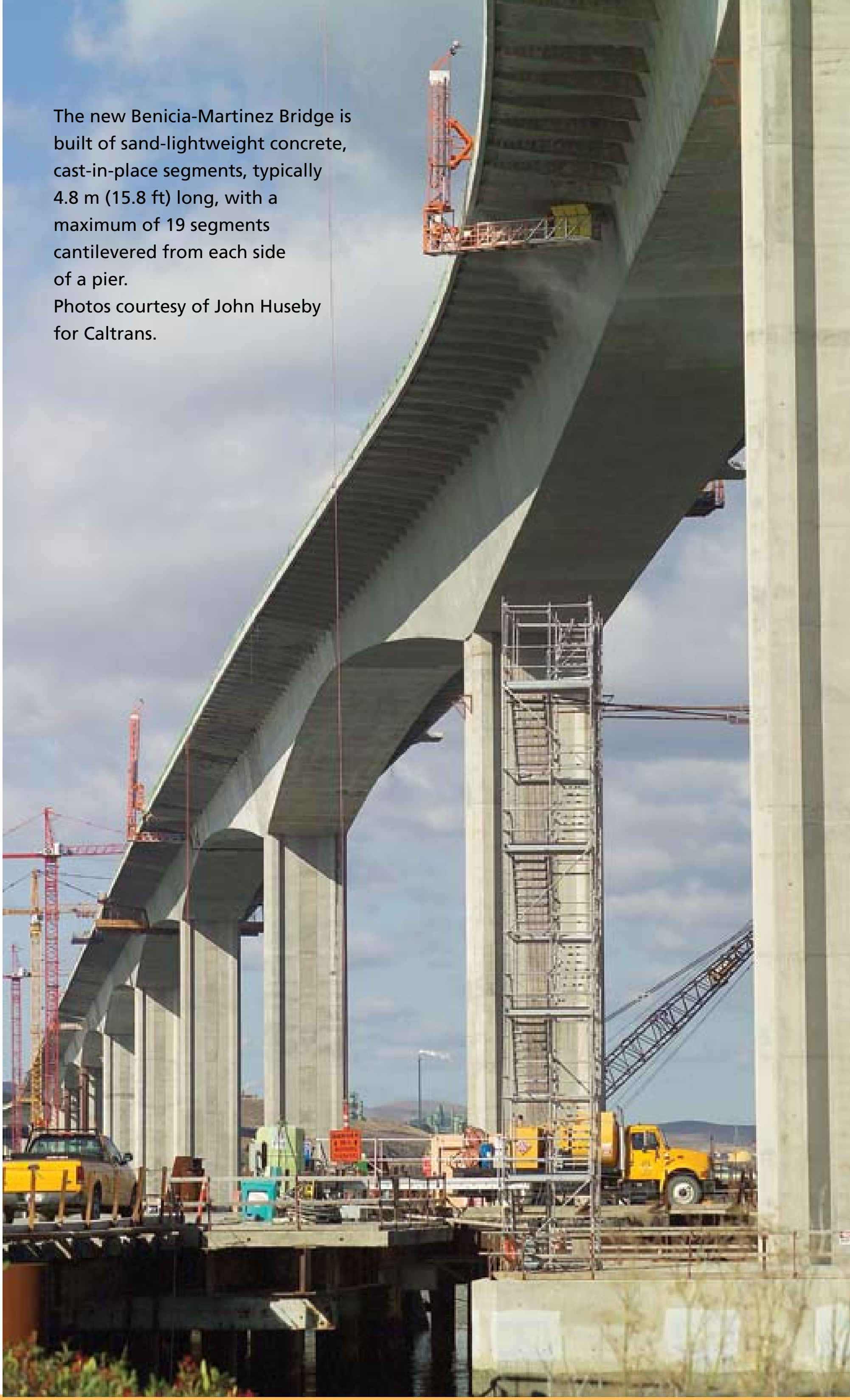
PRIME CONTRACTOR: Kiewit Pacific Co., Martinez, Calif.

CONCRETE SUPPLIER: Kiewit Pacific Co. and RMC Lone Star for the northern elevated approaches

LIGHTWEIGHT AGGREGATE SUPPLIER: Carolina Stalite Company, Salisbury, N.C.

REINFORCING STEEL SUPPLIER: Regional Steel Corporation, Tracy, Calif.

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



The new Benicia-Martinez Bridge is built of sand-lightweight concrete, cast-in-place segments, typically 4.8 m (15.8 ft) long, with a maximum of 19 segments cantilevered from each side of a pier.
Photos courtesy of John Huseby for Caltrans.

by Ganapathy Murugesh,
California Department of Transportation
and Karen Cormier,
T.Y. Lin International

lightweight coarse aggregate to produce concrete that is lower in density than normal weight concrete.

Span lengths on the cantilever portion of Benicia-Martinez Bridge range from 127.4 to 200.8 m (418 to 659 ft). Including the Caltrans-designed northern approach spans, the bridge encompasses 22 spans, with 16 over water. The segment cross section consists of a single-cell box girder with a total depth ranging from 11.4 m (37.4 ft) over the piers to 4.54 m (14.9 ft) at midspan. The top flange has a width of 24.0 m (78.7 ft), while the bottom flange thickness varies from 1.80 m (5.9 ft) at the pier segment to 250 mm (9.8 in.) at midspan.

Designing 200-m (656-ft)-long spans for cast-in-place segmental construction pushes the limits of the construction technique. The segments at Benicia-Martinez are 4.8-m (15.8-ft) long with a maximum of 19 segments cantilevered from each side of a pier. Add in that these long spans were designed for a high-seismic zone, and the bridge becomes the first of its kind—and a world-class structure.

CAST-IN-PLACE, SINGLE CELL, SEGMENTAL BOX GIRDER / CALIFORNIA DEPARTMENT OF TRANSPORTATION (CALTRANS), OWNER

FORM TRAVELER SUPPLIER: VSL

BRIDGE DESCRIPTION: The main bridge is 2266 m (7434 ft) long by 24.0 m (78.7 ft) wide at the deck and is divided into four frames with lengths of 515.8, 644, 811.4, and 290.3 m (1692, 2113, 2662, and 952 ft), plus a short length at one end.

STRUCTURAL COMPONENTS: 344 cast-in-place lightweight concrete segments, 16 piers, 99 foundation piles in water, average height of structure is about 45 m (150 ft) above water

BRIDGE CONSTRUCTION COST: $660 million

Four types of bridges were evaluated during design: a steel-truss bridge; a steel box-girder bridge; a concrete cable-stayed bridge; and a cast-in-place balanced cantilever lightweight concrete segmental bridge. Without factoring in the 150-year lifecycle aspect, the initial cost of the cast-in-place, lightweight concrete, segmental bridge was lower than the other structure types, and it was selected.

Lightweight Concrete Adds Length

The designers and Caltrans evaluated the use of 160-m (528-ft)-long spans on the four bridge types, and that length was used to begin design work on the bridge. But the Coast Guard asked for a 200-m (656-ft)-long span for navigational purposes, and the lengths were changed during final design. The lifeline structure criterion also was included during the final design stages.

The key to achieving the extra span length and satisfying lifeline structure criteria was the use of lightweight concrete. The lighter the segments that can be cast, the less massive is the structure that pushes the piers in a seismic event. But finding the right mix design during construction required countless tests and evaluations of more than 30 concrete mixtures. Caltrans, designers, and the contractor investigated a variety of aggregates, admixtures, cement contents, and water-cementitious materials ratios.

125 pcf Density

As finally designed, the specified concrete has a density of 125 pcf, or about 15 percent less than conventional structural concrete. Designers considered using lightweight sand, which could have produced a concrete density of 110 pcf, but it would not meet all the necessary material property requirements. Using normal weight sand produced concrete with a density in the range of 120 to 125 pcf, which would result in much improved concrete qualities, including higher strength, higher modulus of elasticity, lower creep, and less shrinkage.

With all of the elaborate testing efforts, the design and construction team discovered that to meet the modulus of elasticity requirements, the concrete needed a high cementitious materials content. That gave it a compressive strength of between 10,000 and 11,000 psi, where only 6500 psi was needed by design.

Special aggregates were used to achieve the desired properties. The fine aggregate (Sechelt sand) was imported from Canada and the coarse lightweight aggregate (Stalite) came from North Carolina.

Ice in the Concrete

Due to the high cementitious materials content, the concrete produced a high heat of hydration. Yet the specifications limited the maximum concrete temperature during curing to 71°C (160°F) to avoid delayed ettringite formation. To achieve this, the contractor used ice in the concrete instead of water and cooled the concrete with liquid nitrogen. A long wand with a nozzle was used to inject liquid nitrogen, for a few minutes, into the concrete in the trucks. The combination of ice and nitrogen lowered the initial temperature of the concrete to 40 to 50°F.

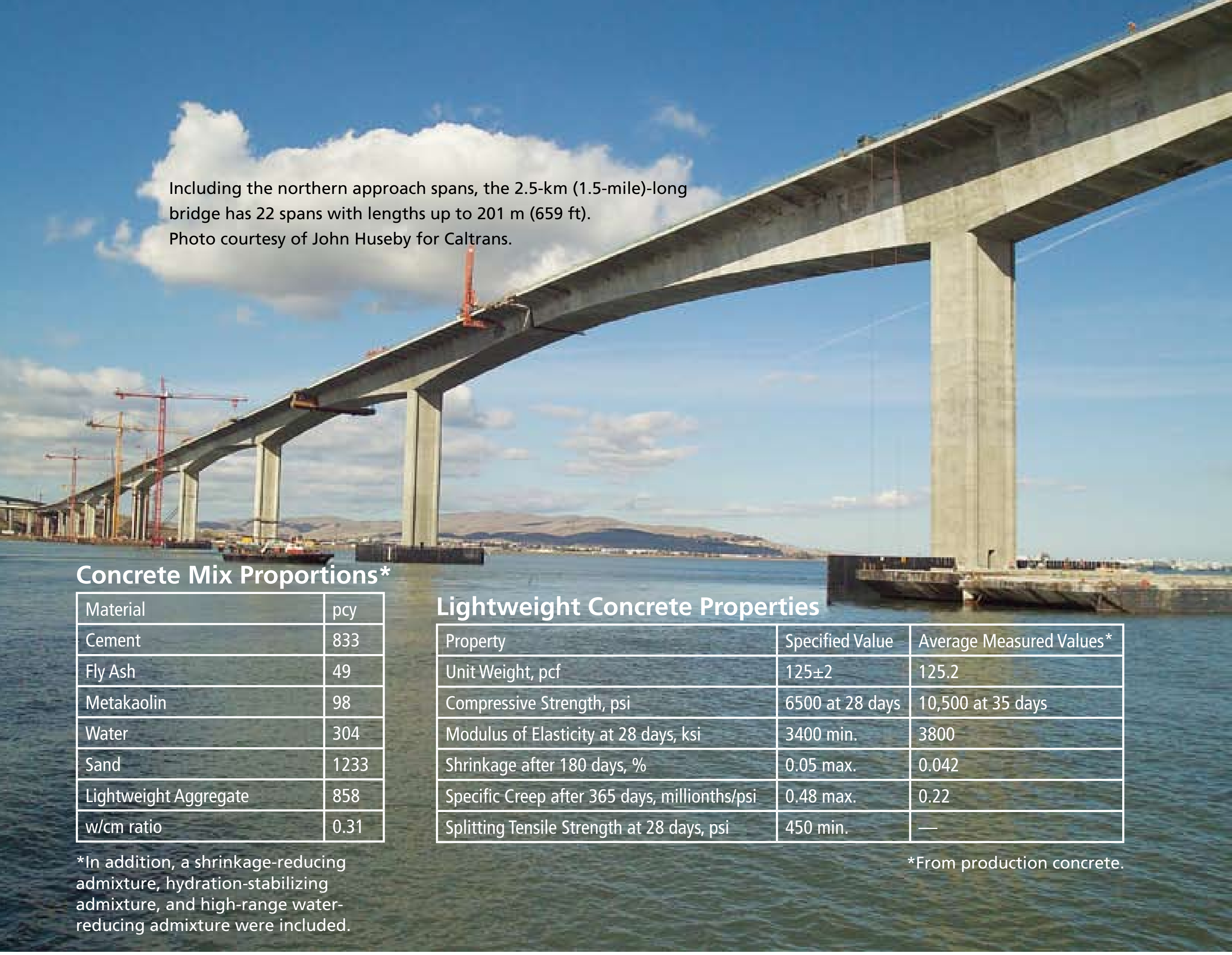
A system of plastic tubes in the segments carried water to cool the concrete during the curing process. Radiator-like tubes ran through the bottom slab, the webs, portions of the top slab, and the connection of the web to the top slab.

Marine placement of lightweight concrete posed additional challenges. The contractor provided an on-site batching plant on the south shore of the Carquinez Strait. Mixing trucks traveled from the batch plant to a barge and drove on board. The barge, which could carry four loaded trucks each time, transported the concrete to the desired pier cantilever location.

'The key to achieving the extra span length and satisfying lifeline structure criteria was the use of lightweight concrete.'

High cementitious materials content created high heat of hydration, so the contractor used liquid nitrogen with a wand to cool the concrete inside the trucks.
Photos courtesy of T.Y. Lin International.

Barges carried concrete trucks to a concrete pumping barge located near the segments being cast. The pump could deliver concrete as high as 55 m (180 ft).



Including the northern approach spans, the 2.5-km (1.5-mile)-long bridge has 22 spans with lengths up to 201 m (659 ft). Photo courtesy of John Huseby for Caltrans.

Concrete Mix Proportions*

Material	pcy
Cement	833
Fly Ash	49
Metakaolin	98
Water	304
Sand	1233
Lightweight Aggregate	858
w/cm ratio	0.31

*In addition, a shrinkage-reducing admixture, hydration-stabilizing admixture, and high-range water-reducing admixture were included.

Lightweight Concrete Properties

Property	Specified Value	Average Measured Values*
Unit Weight, pcf	125±2	125.2
Compressive Strength, psi	6500 at 28 days	10,500 at 35 days
Modulus of Elasticity at 28 days, ksi	3400 min.	3800
Shrinkage after 180 days, %	0.05 max.	0.042
Specific Creep after 365 days, millionths/psi	0.48 max.	0.22
Splitting Tensile Strength at 28 days, psi	450 min.	—

*From production concrete.

For some placements, the barges were secured to the side of another barge with a concrete pump that pumped the concrete vertically to a height of more than 55 m (180 ft). On board the pump barge, the concrete was remixed before being pumped vertically to the placement location.

For other placements, the barges were secured to the side of a footing, where a tower crane raised buckets of concrete to a remixer on the bridge deck from which the concrete was then pumped horizontally up to 100 m (330 ft) to the intended segment. The trial-batch program produced only a few possible mix candidates that satisfied the specified concrete properties, the high early strength, and the flow characteristics to allow wet concrete to be pumped and placed at the segments. High early strength characteristics helped to reduce the segment cycle times and facilitate faster completion of the project.

The structure made use of midspan hinges between the three-span continuous frames, a unique application especially in a high-seismic zone. These elements provide continuity for post-construction loads (live loading and force redistribution) as well as to lock the cantilevers laterally and vertically together for temperature movements and a seismic event. The hinges are comprised of built-up steel box-girder elements installed inside the box-girder superstructure. During an earthquake, the steel girders transmit transverse and vertical forces across the span, yet they still allow independent longitudinal sliding between each adjoining frame.

Substructure Construction

The main-span foundation consists of large prestressed concrete footings, each supported on a pile group of eight or nine cast-in-steel shell (CISS) piles with rock socket extensions. The piles consist of two distinct sections, an upper 2.5-m (8.25-ft)-diameter CISS pile with a permanent steel casing, and a lower 2.2-m (7.25-ft)-diameter cast-in-drilled hole (CIDH) rock socket. Together, the two sections extend up to 80 m (262 ft) into bay mud and rock.

The area's geology and topography presented challenges to pile design and construction. In a confined state, the foundation rock had substantial compressive strength, but in an unconfined state, the material would crumble in your hand. The upper sections of the piles were placed by driving permanent steel casings through mud down to the rock. The contractor then used a Menck MHU 4.5 MN (500 ton) hydraulic hammer, the second largest in the world, to perform the driving operation. All mud and soils were excavated from within the steel shell and the lower rock socket construction

Driving the pile casings set off sound vibrations underwater that led to fish being killed. The contractor devised a bubble-curtain apparatus to place around the casing that produced a curtain of air bubbles to attenuate the sound underwater and protect the fish.

commenced through the cleaned out upper section.

To build the CIDH rock sockets, the contractor initially applied a reverse-circulation drilling method. That approach relies on polymer slurry to support the rock socket holes during drilling. But unexpected caving occurred inside the rock sockets, and it was abandoned. The integrity of the rock sockets was critical, because that portion of the piles provides the maximum friction and bearing capacity. The sockets extended up to 30 m (100 ft) into the rock.

To prevent the rock from crumbling and caving, the construction team identified a subcontractor, Malcolm Drilling, which used a fully-cased rotator drilling operation that rotated a temporary casing to the prescribed rock socket tip elevation. The rock was then removed from inside the casing, the bottom of the hole was thoroughly cleaned out, and reinforcement cages were installed. As concrete was tremied into place around the reinforcement, the contractor withdrew the temporary casing, leaving the concrete in direct contact with the rock.

This rotator method had never been used over water. To permit its use, the contractor built five special work platforms over the existing CISS pile casings. Three platforms were used to build shallow-water piers. Two platforms, with rotators aboard, were used to build the nine deep-water foundations. The platforms each weigh 1800 tons, have nine holes in them for pile installation, and are designed to support the rotator, the digging crane, and other gear. After the rock sockets were completed, the steel-cased upper sections were infilled with reinforcement and concrete.

In addition to the geological demands placed on the substructure construction, the steep rock planes sloped upward from the center of the channel toward land at about a 70-degree angle. This topography demanded deeper, taller columns in the bridge's center section and shorter columns on the landward sides. Generally speaking, tall columns are more flexible, and shorter columns are stiffer. Yet design principles required that all columns have the same stiffness in the event of an earthquake.

One solution was to install steel isolation casings in the mud and rock around the shorter columns. By placing an air gap between the shorter columns and the external casing, those columns can display unrestricted, flexible behavior during a seismic event. Another solution was to simply reduce the cross-sectional area of the shorter columns.

Protecting the Environment

Immediately after the start of CISS pile-driving operations, the remains of several Delta Smelt, Sacramento Split Tail, and Salmon fish washed up on the shore. The project team quickly determined that the pile-driving noise was harming the fish. Pile driving was immediately discontinued, and the problem threatened to stop the project.

To overcome this obstacle, the contractor worked with Caltrans and other designers to create a bubble-curtain apparatus consisting of a steel framework with pipes, which could be placed around a pile. The apparatus was constructed using four separate quarter-circle sections to facilitate installation down through the pile casing template. Each quarter section of the apparatus consisted of finely perforated circumferential pipe at 5-ft spacing, all connected to a main vertical pipe and supported on a steel frame.

During pile driving, four quarter-circle bubble curtain devices were installed around the steel casing. Air from a compressor was pumped down the vertical pipes into the circumferential pipe to produce a bubble curtain around the pile casing. The bubble curtain provided excellent sound insulation and successfully reduced the sound by 25 to 30 decibels. The result: the fish were protected and construction could proceed.

It required considerable teamwork among the designer, the contractor, and the owner to bring this bridge to a successful conclusion. Issues including concrete mixture design, high heat of hydration, and difficulties with CIDH piles were solved in the design and construction of the Benicia- Martinez Bridge. The innovative techniques discovered and applied in this bridge could also be applied to similar projects in the industry.

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30th pti ANNIVERSARY

PTI's Bridge Activities

Established in 1976, the Post-Tensioning Institute (PTI) is recognized as the worldwide authority on post-tensioning and is dedicated to expanding post-tensioning applications through marketing, education, research, teamwork, and code development while advancing the quality, safety, efficiency, profitability, and use of post-tensioning systems.

PTI's bridge activities include:

- *6th Edition of the Post-Tensioning Manual*—this major update includes two new chapters on bridges and stay cables.
- *Grouting Specification*—developed by PTI's Grouting Committee, this new specification represents a major advance in post-tensioned construction.
- *Recommendations for Stay Cable Design, Testing and Installation*—these recommendations serve as the standard for cable-stayed bridge construction around the world.
- *Certification – Bonded Tendon Installation*—this comprehensive training and certification program is intended for all field personnel involved in the installation of bonded post-tensioning, including installers, inspectors, and construction managers.

The *PT Journal* is published semiannually and often includes papers on durability and bridge design. PTI also sponsors an annual technical conference to showcase the latest in post-tensioning technology.

For more information on PTI, please visit www.post-tensioning.org.

A WHOLE new cast

by Wayne A. Endicott

Innovative concrete used on Iowa bridge eliminates reinforcement and creates new concept for precast concrete bridges

When Neil Armstrong took his first historic step on the moon in 1969, he declared it to be "One small step for a man, one giant leap for mankind." Perhaps the bridge builder's equivalent of that "giant leap" was taken recently on a small rural stretch of highway in Wapello County in the southeastern corner of Iowa, where a new concrete material offers great potential for future bridge designs.

The Wapello County Mars Hill Bridge comprises three 110-ft-long precast concrete modified 45-in.-deep Iowa bulb-tee beams topped with a cast-in-place concrete bridge deck. The concrete offers such considerable strength that the beams were built without any shear reinforcement. The ultra-high performance concrete (UHPC), called "Ductal," was supplied by Lafarge North America and achieves up to 30,000 psi compressive strengths, with ductility.

Originally developed in France a decade ago, UHPC is produced with materials commonly found in concrete such as cement, silica fume, sand, high-range water-reducer, and water, plus other unique materials like ground quartz and steel or PVA (polyvinyl alcohol) fibers.

profile

MARS HILL BRIDGE / WAPELLO COUNTY, IOWA

ENGINEER: Iowa Department of Transportation, Ames, Iowa

GENERAL CONTRACTOR: Bloomfield Bridge and Culvert, Inc., Bloomfield, Iowa

PRECASTER: Lafarge Canada Inc., Winnipeg, Manitoba, Canada, a PCI-Certified Producer

BRIDGE DESCRIPTION: 24-ft 6-in.-wide by 113-ft-long single-span bridge

Lafarge cast the Ductal beams at its Winnipeg, Manitoba, Canada plant. The beams were then trucked to the site for installation. Photos in this article courtesy of Kenneth F. Dunker and Brian P. Moore.

The beam dimensions were reduced compared to typical Iowa bulb tees.

Depending on the curing process, compressive strengths higher than 18,000 psi can be achieved, according to Brian Moore, Wapello County Engineer. The UHPC that was used for the bridge contained steel fibers (approximately 2 percent by volume), eliminating the need for nonprestressed reinforcement.

The Wapello County bridge represents the first highway bridge in North America to utilize the material, although it has been used in other applications. In addition to eliminating the need for structural reinforcing steel, a bridge built with UHPC can be built with longer, thinner, more aesthetically pleasing beams, according to Dean Bierwagen, Project Engineer for the Iowa Department of Transportation (IDOT).

Collaborative Effort

The bridge resulted from a collaborative effort among several groups, including the Federal Highway Administration (FHWA), IDOT, Iowa State University (ISU), and Lafarge. The county became involved when IDOT and ISU proposed that it could help prove the efficacy of the UHPC construction system for a highway bridge. County officials needed to replace an existing bridge at the Mars Hill location and thought it would make a strong candidate, according to Moore.

Using UHPC for the design gained impetus when the county received a $300,000 award through the FHWA's Innovative Bridge Research and Construction Program to demonstrate the use of the concrete. The project got the go-ahead from the Wapello County Board of Supervisors, which then entered into an agreement with the university after accepting the award.

A major hurdle concerned design specifications, Bierwagen says, since there were no other existing highway bridges in North America that demonstrated the new concrete's high compressive strength. That was one of the primary reasons the FHWA showed such interest in the project. "The FHWA is looking for projects like this that can aid in developing guidelines for the design of future bridges employing this material."

As design proceeded, Bierwagen's team reduced the dimensions of the beams compared to typical Iowa bulb tees. The web thickness was reduced from 6½ in. to 4½ in., the bottom flange from 7½ in. to 5½ in., and the top flange dimension from 3¾ in. to 2¾ in.

An 8-in.-thick cast-in-place concrete deck was used on top of the modified bulb-tee beams.

PRECAST CONCRETE MODIFIED 45-IN.-DEEP IOWA BULB-TEE BEAMS TOPPED WITH A CAST-IN-PLACE CONCRETE BRIDGE DECK / WAPELLO COUNTY, OWNER

STRUCTURAL COMPONENTS: Three modified 45-in.-deep Iowa bulb-tee beams cast with ultra-high performance concrete topped with an 8-in.-thick cast-in-place concrete deck

BRIDGE CONSTRUCTION COST: $432,000

The concrete's attributes could change the way bridge engineers approach designs.

Exploration Took Three Years

Because of the material's unique attributes, exploring the potential of the Ductal concrete continued for nearly three years. This resulted from an extensive testing program, which was further challenged by the need to certify the ability of a suitable precasting plant to manufacture the beams.

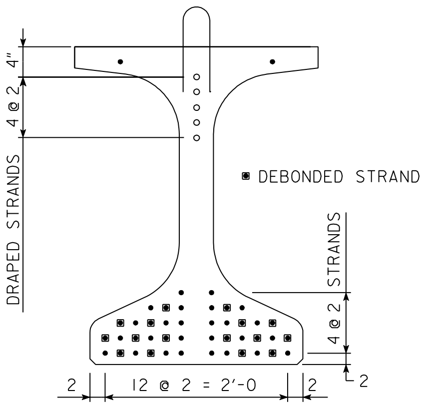
So that IDOT and other project collaborators could gain confidence with the technology, a test mix was made at its Materials Laboratory in Ames, Iowa. Once the laboratory tests were completed, the process of certifying a plant to cast the beams began. Plant inspections of local precasting plants and test batches were performed at two local plants.

Bids received from those plants following the testing phase were higher than expected, owing to the steep learning curve. To help overcome that concern and take it out of the equation, the team selected Lafarge's precast team in Winnipeg, Manitoba, Canada, which possessed valuable knowledge and prior experience with the material.

The next stage involved casting a 17-ft-long test beam. Also, to verify shear and flexural performance, 10- and 12-in.-deep shear beams were cast. Testing verified the service performance under flexure and the ultimate shear strength, so the go-ahead was given to cast the 110-ft-long production beams.

The full-size bridge beams were prestressed using 0.6-in.-diameter, low-relaxation strands. Eliminating the shear reinforcement meant the only nonprestressed reinforcement in the beams was U-bars connecting the 8-in.-thick cast-in-place deck to the precast beams. The final beam design section had 49 prestressing strands stressed to 72.6 percent of ultimate strength. To reduce stresses at the ends of the beams, five strands were draped along with the debonding of 16 other strands, Bierwagen says.

The U-bar option was chosen over two other possible connection systems. One involved the installation of top shear studs after beams were cast and the other used a dowel-bar splicing system installed after casting. These options were examined to develop the best method to achieve an acceptable shear transfer between the beam and the cast-in-place concrete, while facilitating the required casting and curing procedures. Once cast, the beams were immediately covered with a plastic sheet to complete the curing process.

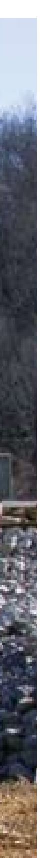


Each beam contains forty-seven 0.6-in.-diameter, low-relaxation prestressing strands in the bottom flange stressed to 72.6 percent of ultimate strength. No shear reinforcement was used.

The new Wapello County Mars Hill Bridge, 113-ft-long and 24-ft 6-in.-wide, features three 110-ft-long modified Iowa bulb-tee beams manufactured using ultra-high performance concrete.

One crane at each end removed the beams from their transport vehicles and set them into place.

The material's high compressive strength allowed bridge designers to create a lower profile bridge by using longer, thinner beams.



Highly Impermeable Concrete

In addition to designing lighter weight beams with more slender cross sections and no reinforcement, this revolutionary concrete provides an added advantage in that it is highly impermeable, thereby reducing the threat of corrosion within the structure. "This should provide a longer lifespan for bridges subjected to moisture and the effects of road salt," Bierwagen points out.

This project represents only the beginning of the use of this UHPC system in bridge designs, which could change the way bridge engineers approach designs, says Vic Perry, Vice President and General Manager for Ductal at Lafarge North America. "We think it will be possible to build an entire bridge, including the deck, without reinforcement. This bridge represents a first step in that process. Ductal provides a real synergy with the prestressed concrete industry." The material also provides an opportunity to create slender, long-span beams and more graceful bridges without the need for reinforcing bars, he notes.

The FHWA is looking for projects like this to aid in developing guidelines.

Another key advantage was the speed with which the bridge was completed after the testing was verified. Casting the 110-ft-long beams was completed in June and July of 2005, and construction began in August. By the following February, the bridge was opened to traffic. The beam spacing was 9-ft 7-in., with 4-ft overhangs, creating a 24-ft 6-in.-wide completed structure.

Moore is not bashful about his admiration of the system. "I see a tremendous potential here. The use of steel fibers and the elimination of reinforcement allow us to use a dense material without the concerns of corrosion." Lauding the success of the project, Moore, like Perry, suggests that the next logical step is to create an entire bridge, including the deck, with Ductal concrete. The successful Mars Hill Bridge project has the team that created the bridge already looking for more projects that can take advantage of the system, Moore says. This includes a bridge in Buchanan County.

For more information on this project visit www.wapellocounty.org/roads/marshill.htm or other projects, visit www.aspirebridge.org.

Veterans' Glass City Skyway

Toledo's Newest Landmark Ready to Shine

by Michael Gramza, Ohio Department of Transportation and Jeff Walters, FIGG

By mid-2007 drivers on I-280 through the heart of Toledo will see the city from new vantage points 136 ft above the Maumee River. A striking cable-stayed signature bridge, featuring a single 400-ft-tall central pylon and twin 612-ft 6-in. spans, is the result of a vision begun nearly 20 years ago by the Toledo Metropolitan Area Council of Governments (TMACOG). The $220 million structure will soon be completed under the administration of the Ohio Department of Transportation (ODOT). The top of the sculpted pylon delivers on a public expectation to showcase glass, reflecting on Toledo's industrial heritage of glass manufacturing. Except for 3 ft at the top, the uppermost 199 ft of the pylon is clad on all four sides in specially manufactured glass. The glass is designed to reflect the sky during the day and shine with more than 16 million color combinations across the skyline at night, courtesy of hundreds of LED fixtures.

To deliver on the public's direction during FIGG Bridge Design Charettes™ required:

- Innovation to create the cable-stayed cradle that conveys the largest stays in the world (156 strands) through the pylon;
- Persistence to determine how glass could creatively be showcased on a transportation project;
- Exacting dedication to the idea that this landmark bridge would shine over Toledo for more than 100 years; and
- Be bid within the budget.

To create this unique and lasting landmark, the FIGG team worked closely with ODOT and the Program Management Consultant (PMC), a joint venture of HNTB and Parsons Brinckerhoff. Linda Figg, President/CEO of FIGG appreciated the importance of ODOT's overall plan, saying, "Through the vision and talent of the Ohio Department of Transportation, a team came together to achieve success for the community. ODOT understood the importance of the communities' voice in achieving a landmark bridge."

Interstate 280 currently crosses the Maumee River in the heart of Toledo on the Craig Memorial Bridge, one of the few remaining movable bridges on the interstate system. An average of

profile

VETERANS' GLASS CITY SKYWAY / TOLEDO, OHIO

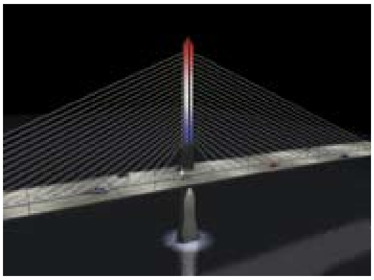
BRIDGE DESIGNER/CONSTRUCTION ENGINEERING INSPECTION: FIGG, Tallahassee, Fla.

PROJECT MANAGER CONSULTANT: HNTB/Parsons Brinckerhoff, Toledo, Ohio

CONTRACTOR: Bilfinger Berger Civil, Inc., Vancouver, Wash.

CONCRETE: Integrated Resources, Inc.—a division of The Stansley Group, Toledo, Ohio and Kuhlman Concrete, Toledo, Ohio

LED fixtures behind the 193 ft of glass on the pylon can be programmed for 16.7 million color combinations.



New engineering innovations are sure to be replicated on other projects.

900 annual openings of the bascule span stops interstate traffic. In 1988, TMACOG identified the replacement of the existing bridge as its highest transportation priority for the northwest Ohio region. A new high-level bridge would ease traffic congestion on I-280 and maintain shipping to the Port of Toledo. By retaining the existing bridge for local vehicular and pedestrian traffic, the project would also facilitate commerce within the City of Toledo by effectively adding another local crossing over the Maumee River.

The new high-level bridge would create a signature focal point and landmark for the city and the surrounding area. Toledo has a rich history in manufacturing, specifically in the production of glass. Several of the largest glass companies in America have been located, and continue to operate, in the Toledo area. Combining the two—a new bridge and an industrial heritage in glass production—would produce a new landmark and symbol for the future of Toledo.

The Community Speaks

In April and May of 2000, a series of community design charettes was held with representatives from ODOT, the Toledo Arts community, the PMC, the Maumee River Crossing (MRC) task force, neighborhoods, and the media. The MRC task force represented the cities of Toledo and Oregon, Lucas County, the Toledo-Lucas County Port Authority, TMACOG, and ODOT. They determined that the new bridge would have a precast concrete segmental superstructure, a cable-stayed main span providing 120-ft vertical and 400-ft horizontal clearances, a six-lane roadway, and world-class aesthetics built around a theme of "Glass."

Concrete was selected as the preferred material to meet the structural and aesthetic demands of the project. Precasting was preferred to allow for construction with minimal traffic disruption in the congested urban corridor of the project site. Further, the task force made several recommendations for the main span aesthetics, focused on achieving a structure that would be light, simple, and elegant in appearance. With that direction, FIGG presented options in the first design charette on which the participants voted their preference by scoring 1 for 'not preferred' to 10 for 'highly desirable.' By votes of nearly three to one, a single plane of stays was favored due to the resulting clean lines and dramatic appearance.

The participants selected a combined fan/harp arrangement for the stays, a classic layout that provided structural efficiency while building on the task force's adopted motto "Look Up, Toledo." Participants strongly preferred a structural scheme featuring a single pylon, rather than multiple smaller pylons, commenting that it would be more dramatic and make the strongest statement by providing the greatest visibility in the relatively flat Toledo area. As the participants began to weigh in on pylon characteristics, the enthusiasm in the room intensified—everyone recognized that this was perhaps the best opportunity to make a strong statement about Toledo. Participants nearly universally ranked the use of glass with a score of 9 out of a possible 10, and the upper pylon, with views from all parts of the city, as the preferred location.

Aesthetic lighting on the bridge was to be focused on the stays and the pylon, with the opportunity to create special lighting for events in the city. Two general pier shapes were selected for further development—curved and rectilinear, with those general shapes required to be consistent with the pylon's appearance. The design choices even focused on the driving experience, and participants selected a partially open traffic railing to balance openness of views with a desire to provide a 'safe' feeling for drivers.

Use of stainless steel as stay cable sheathing material was desirable because it further advanced and complemented the industrial theme of "Glass." The life-cycle costs relative to other sheathing materials also figured in the selection of stainless steel. Consistency of color between all concrete elements was deemed important to the project's overall aesthetic impact.

Based on these initial outcomes, FIGG developed numerous aesthetic schemes, which were reviewed by ODOT and MRC task force. The outcome of the second community design charette was to move into final design with the rectilinear pylon with a prismatic shape and octagonal piers for the approaches and ramps, resulting in consistent aesthetic characteristics carried throughout the 2.75 miles of ramps, elevated

SEGMENTAL / OHIO DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: An 8800-ft-long structure including a cable-stayed bridge with a single 400-ft-tall pylon supporting twin 612-ft 6-in.-long spans with a single plane of cables.

STRUCTURAL COMPONENTS: 3050 precast concrete elements including 42 concrete delta frames, 185,000 cu yd of concrete, 1.9 million pounds of post-tensioning strand, and 32.6 million pounds of reinforcing steel

Work nears completion just prior to the erection of the final segments.

Erection of a precast concrete delta frame that transfers the loads from the segments to the cables.

roadway, and the cable-stayed main span. Marc Folk, Executive Director of the Arts Commission of Greater Toledo participated in the project design efforts and summed up the bridge design process by saying, "The willingness of FIGG to engage the community in the dialog of aesthetics of the bridge has been an overwhelming success. Not only have these aesthetics been integrated into the project, they have also led to new engineering innovations sure to be replicated on other projects. Incorporating these elements into the bridge has given this project a unique, forward thinking community identity that will be enjoyed by our citizens for generations to come."

A Concrete Solution

Innovative solutions were necessary to deliver this unique bridge. Urban congestion and limited available right-of-way, typical in large cities, surround the bridge site. It was essential that construction be accommodated within a relatively small footprint and have minimal impact on the neighborhoods and businesses around the site. Precast concrete segmental technology minimized this impact by effectively moving much of the construction work to an off-site casting facility. The selection of concrete as the primary building material provided benefits to the local Toledo economy because local companies could provide materials and trades personnel to construct the bridge.

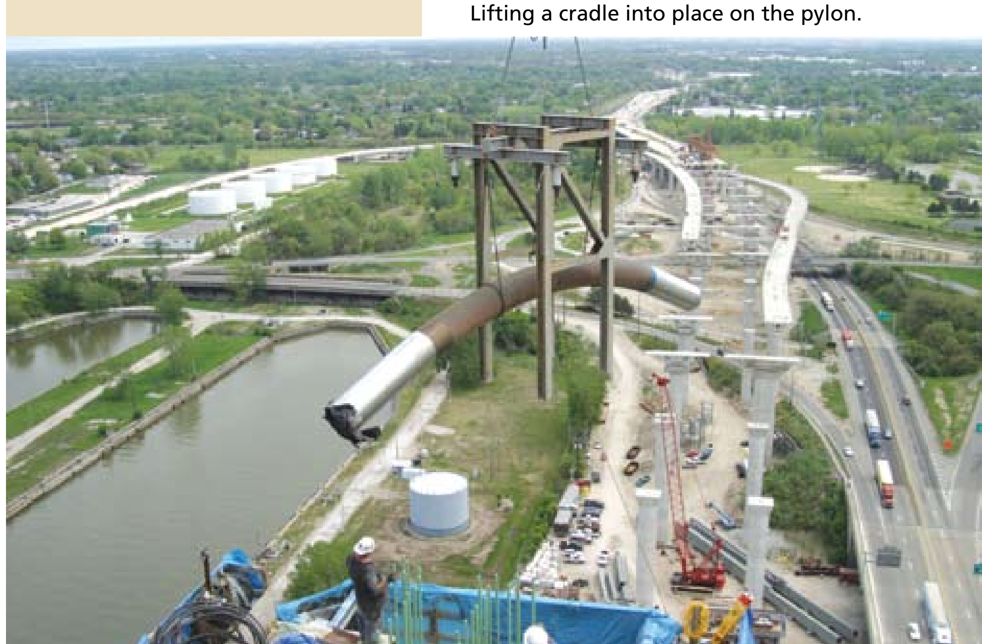
High performance concrete provided the means to achieve the structural requirements of strength, durability, and workability while providing the aesthetic features expected by the community. High compressive strength concrete was necessary to minimize structural member sizes while creating sculpted pier and pylon shapes. In the superstructure, a minimum compressive strength of 6000 psi was specified for the piers and superstructure segments, while 8000 psi was determined to be optimal for the main span segments. Once casting of the 3050 segments began, the contractor found that by using the 8000 psi mix for all superstructure segments, forms could be stripped more quickly, compressing the overall casting schedule. The pylon, which reaches 400 ft above the Maumee River, was cast from 10,000 psi high performance concrete.

Concrete for all superstructure segments, the piers, and the pylon was specified to have a maximum permeability of 1000 coulombs at 28 days and a plastic air content of 5 percent. The superstructure segments included a 1.5-in.-thick integral wearing surface, cast with the segments and post-tensioned along with the

Collaborative Process

The collaborative process on this project is best expressed by the words of Dave Dysard, now Deputy District Director for ODOT District No. 2 "The Veterans' Glass City Skyway demonstrates the strength of a truly collaborative process in an urban region. Staff and local government representatives worked through TMACOG, the metropolitan planning organization for the area, to identify and document the need for the project in the regional planning process. The regional plan placed the project as the top priority in the area. Local government agencies formed a broad-based task force with government business and neighborhood representatives to develop specific project alternatives. ODOT agreed to take on the project and continued working with the task force to design and build a landmark structure that will be an icon of the resurgence of this region."

Lifting a cradle into place on the pylon.



Specially designed and manufactured glass panels are being installed on the four sides of the pylon and installation will be complete prior to the bridge opening to traffic in early summer.

The Skyway demonstrates the strength of a truly collaborative process.

structural section, further enhancing driving surface durability by minimizing cracking. The use of an integral wearing surface also eliminated the need for a costly overlay to be applied during construction, saving both money and time.

Creating the Cradle

A single plane of stays could be accomplished utilizing precast concrete delta frames—FIGG had incorporated this innovation on other cable-stayed bridges including the I-295 Varina-Enon Bridge near Richmond, Virginia, and Delaware's Chesapeake & Delaware Canal Bridge. The challenge would be combining the slender pylon shape selected by the community with the largest bridge cable stays in the world—156 strands, an increase of more than 70 percent over that previously used in the United States.

Several previous cable-stayed bridge designs utilized a saddle in the pylon to carry the strands; however, given the significant increase in the number of strands, a new system was needed. Utilizing anchorages in the pylon would have resulted in increasing the pylon width by more than a third, from 23 ft to 31 ft. This would increase the overall quantity of materials and possibly the construction costs, but would stray from the preferred slender, elegant shape. Using anchorages in the pylon would also require that operations, critical to stressing, take place as much as 230 ft above the bridge deck, increasing the contractor's potential risk and the cost of the project.

By focusing on the need to allow each strand to act independently, Denney Pate, FIGG Senior Vice President/Principal Bridge Engineer, arrived at the idea of isolating each strand in its own curved 1-in.-diameter stainless steel sleeve within a steel cradle. Pate's approach resulted in a cradle design that allowed each epoxy-coated strand to act independently. While the spaces between the sleeves inside the cradle are grouted prior to the cradle being cast into the pylon, the individual strands remain ungrouted. The stay force—a sum total of the force in each strand—is then transferred into the pylon through radial compression, taking advantage of concrete's natural compressive strength, minimizing reinforcement requirements, and eliminating the need for a large and expensive steel anchorage box within the pylon.

"Cheese plates" at each end of the cradle, along with centering plates located in the curved section of the cradle, maintain the relative positions of the sleeve pipes containing the individual strands. The ends of the sleeves are flared to ease strand installation. The strands are housed within the stay cable sheathing for their free length, while the cheese plates and anchorages keep the strands parallel. ODOT prepurchased the entire stay cable system to facilitate the stay system fatigue testing required by the Federal Highway Administration, removing this testing from the contractor's list of responsibilities, and the project's critical path.

By December 2001, all fatigue tests were successfully completed, including:

- Axial fatigue and ultimate static tests on 82- and 156-strand specimens;
- Axial fatigue and leak test on a 119-strand specimen;
- Single strand cradle sleeve testing; and
- Axial/flexural fatigue test on a 119-strand stay and cradle specimen.

"Many other cable-stayed bridges will benefit from the advancements in technology achieved on this bridge," states FIGG's Pate.

Shining Brightly

During the public meetings, there was strong support for drawing attention to the upper pylon, using glass in the pylon, and incorporating feature lighting. By combining these ideas, a design that uses a 1.2-in.-thick laminated glass composite section incorporating layers of heat-strengthened glass and bonding materials will be installed over a height of 196 ft beginning 3 ft below the top of the pylon. This glass 'sandwich' is mirrored on 1/3 of its surface area to reflect the sky during the day and allow backlighting from LED fixtures behind the glass to illuminate the pylon and shine across the Toledo skyline at night.

A total of 384 low energy LED fixtures are located in the concave recesses behind the glass panels on all four sides of the pylon. LED technology has rapidly moved forward, increasing the durability and life of the fixtures, while becoming even more affordable, providing ODOT with an efficient feature lighting system that will shine brightly with minimal maintenance.

Each fixture is individually controllable via computer software and can produce up to 16.7 million different colors, giving the Toledo community the ability to select both static and moving light displays to mark any holiday or special event. Various color schemes are preprogrammed such as red and green for the Christmas holidays and red, white, and blue for the Fourth of July. Possibilities include showcasing regional sport team's colors on two sides of the pylon until game time and rewarding the victor with the entire pylon in their colors. The ideas and options for pylon lighting colors are nearly endless, providing Toledo with their much-desired landmark bridge to celebrate their city and industrial heritage.

Cast in Concrete

On January 15, 2002, ODOT opened bids for the project and subsequently awarded the construction contract to Fru-Con Construction Corporation (now Bilfinger Berger Civil, Inc.) for $220 million, making the new river crossing and its surrounding contracts the largest project ever undertaken by ODOT. Construction work began in earnest in the spring 2002, with the establishment of a casting yard to produce 3050 precast concrete elements, including 42 concrete delta frames, required for the approach, ramp, and main span. An average of 35 segments was cast each week during reasonable temperatures, 25 per week during cold weather. Approximately 32.6 million pounds of reinforcing steel and 1.9 million pounds of post-tensioning strand have been incorporated into the 185,000 cu yd of concrete to make Toledo's landmark bridge a reality.

On December 20, 2006, the final two segments were placed in the main span. The final main span closure on February 16, 2007, made the 8800-ft-long bridge continuous from end-to-end. Plans are being made by the MRC task force and ODOT for a ribbon cutting and opening of the bridge. The end is in sight—and it's shining brightly. Traffic is anticipated on Toledo's postcard-perfect bridge by summer 2007.

Michael Gramza is Project Manager with the Ohio Department of Transportation and Jeff Walters is Regional Director with FIGG.

For more information on this or other projects, visit www.aspirebridge.org.

AESTHETICS **COMMENTARY**

by Frederick Gottemoeller

The Veterans' Glass City Skyway has to be understood first of all as an expression of civic will and civic pride. The project aims to do more than build a bridge, as important as that bridge might be. Of course, the project will relieve traffic congestion caused by the original routing of I-280 across the Craig Memorial Bridge. However, it will also reconnect neighborhoods that were severed when I-280 was built, catalyze the shoreline development and redevelopment of an important stretch of the Maumee River, and give Toledo, Ohio, and all northwestern Ohio a new symbol of growth and optimism.

Public agencies are often unwilling to accept project objectives beyond the narrowest possible definition of functional transportation. The Ohio Department of Transportation and local communities are to be congratulated for recognizing that a major transportation facility in an urban area is an inseparable element of the urban fabric, that it, therefore, facilitates (or inhibits) transportation, land use, urban design, and symbolic functions; and that efforts to improve all of these functions are legitimate uses of public transportation funds.

With this in mind, the community helped to define parameters for both the bridge and for the areas below and beside it. Parks are being built as integral parts of the project to fill the land areas vacated by I-280 and the area directly below the bridge. By providing centers of positive activity and attractive amenities, the parks will stitch together the severed neighborhoods and provide an impetus for their improvement and redevelopment. They also will provide an attractive backdrop for the bridge itself.

The choice of segmental concrete box girders for the approaches supports the desired park development. The girders provide a smooth, solid, and light colored "ceiling" for the spaces in the park. The wide overhangs and the light color will promote the penetration of sunlight into the parks. The box girders allow piers with single, slim shafts that keep views through the parks open and unobstructed. The piers have been provided with graceful capitals that allow the shaft to stay thin while still accommodating two bearings at the top.

That brings us to the main span itself, and here the shift is from the neighborhood scale to the scale of the Maumee River, the city itself, and indeed all of the locations from which the bridge and its pylon are visible. The first thing to notice is that the deck girder is the same size and shape as the approach girders, so that the one flows smoothly into the other, and the entire bridge seems of a single piece. The second thing is how the tapered facets of the lower part of the tower simulate the piers of the nearby drawbridge, creating a similar image of graceful mass and solid support. The third thing to notice is how these facets smoothly transition above the deck into a needlelike tower made to appear even thinner by the vertical lighted glass. The details of the tower show that this is accomplished while still keeping the load-bearing elements of the tower structurally efficient. The full impact of the pylon will be at night when the lighting is functioning, making it even more memorable.

Finally, to fully understand the impact of the bridge one has to shift scales once again, to the scale of the whole greater Toledo region; everywhere within the advertising reach of the Toledo newspapers and broadcasting stations. The region's residents will see frequent images of the bridge in newspaper articles, in backgrounds of TV shots and in advertising brochures. It will become a symbol of the place where they live and, in some small way, part of their own self-image. It will also be recognized as a symbol of the Toledo region when it appears in national media. The Veterans' Glass City Skyway will join Boston's Zakim Bridge and Tampa Bay's Sunshine Skyway as new bridges that are now nationally recognized symbols of the places where they were built.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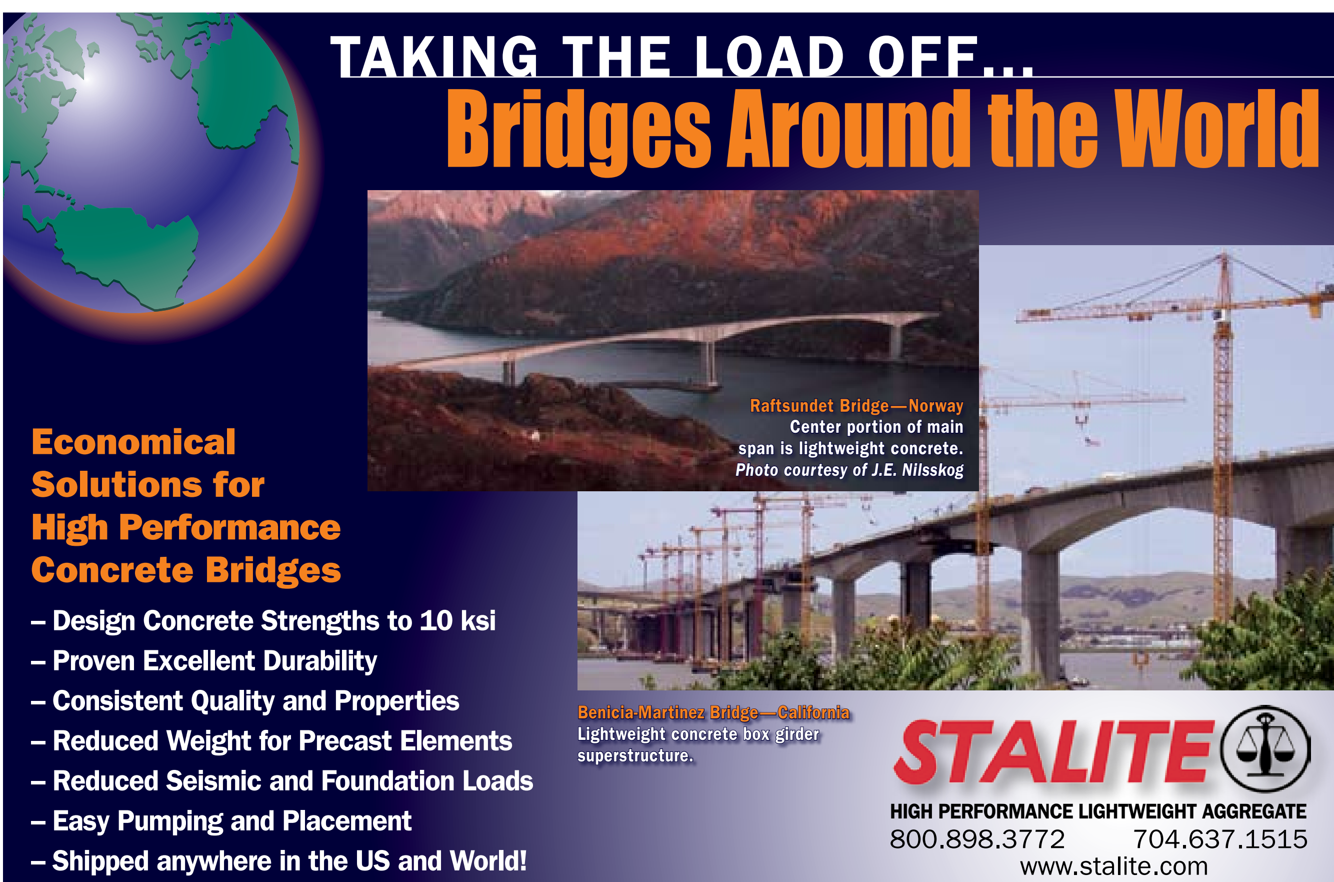
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Raftsundet Bridge—Norway
Center portion of main span is lightweight concrete.
Photo courtesy of J.E. Nilsskog
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Enhancing the 'Bread and Butter'

by Joan D. Bowser, Zann Jones, Jimmy D. Camp, and Robert Meyers, New Mexico Department of Transportation

Typical New Mexico bridges use innovative designs featuring precast concrete U-beams and cast-in-place concrete decks

Intricate and creative designs for once-in-a-lifetime bridges garner awards and acclaim, but designers are most in need of ideas for the typical bridges they design and build every day. The Guadalupe County I-40 Overpass bridges, a set of three structures, gave designers with the New Mexico Department of Transportation an opportunity to solve recurring problems, create strong aesthetic appeal, improve durability, and stay under budget. The design, featuring precast concrete U-beams and cast-in-place concrete decks, provides a strong option for many future bridges.

The new structures, which cross I-40, replaced bridges that were functionally obsolete and structurally deficient. Two of the bridges carry local traffic on minor arterial roads, while the third carries U.S. Route 84. The new structures were offset from the original bridges allowing free design within standard roadway parameters. A cross section consisting of two 12-ft-wide lanes with 6-ft-wide shoulders, for a total roadway width of 36 ft and a bridge width of 39 ft, met the standards for the arterial roads. Eight-ft-wide shoulders were required on the U.S. Route 84 bridge, creating a total roadway width of 40 ft and bridge width of 43 ft.

Interstate 40 carries many travelers and tourists, and the bridges welcome people to the state and to Guadalupe County. To enhance that welcome, strong aesthetics were desired for these bridges. The design also had to reflect the local color of the area and be tied together to establish continuity.

Identical Structures Created Efficiency

The designers decided that the easiest way to approach this challenge was to create identical structures for all three bridges, so artwork could then reflect each locality, while the bridges provided continuity. As a result, the design had to fulfill the requirements for all three bridges. This task was simplified because the interstate highway maintained a consistent width throughout the project length. After considering a variety of options, the designers decided to create two-span bridges with a pier in the center of the median.

Large, unconstrained areas of slope paving on steep slopes have created problems in the past, so the team was asked to avoid using steep slopes constrained by slope paving as the support at abutments. Using self-stable slopes would have added 50 to 60 ft to each roadway side, creating spans of about 150 ft, which would have required an increase in road height of 9 in. or more. Mechanically-stabilized earth (MSE) walls proved to be a better value economically and were thought to have better aesthetic potential for the given

profile

GUADALUPE COUNTY I-40 OVERPASS BRIDGES / GUADALUPE COUNTY, NEW MEXICO

ENGINEER: New Mexico Department of Transportation, Santa Fe, N.M.

PRIME CONTRACTOR: Reiman Corp. subcontracted to James Hamilton Construction Co., Silver City, N.M.

MSE WALL SUPPLIER: Costillo Ready Mix Concrete, Inc., Belen, N.M.

PRECASTER: Coreslab Structures Inc. (formerly Rinker Materials), Albuquerque, N.M., a PCI-Certified Producer situation. MSE support was chosen using a 9-ft 6-in. setback from the face of the support to the centerline of the bearing, creating two spans of 105 ft 8 in. for each bridge.

Prestressed concrete U-beams were selected because of their form as well as for structural stability. Four 54-in.-deep U-beams were used rather than five 63-in.-deep I-beams to obtain the required clearance with minimal fill requirements. The U-beams were designed using a concrete compressive strength of 9500 psi with a release strength of 5500 psi—a standard New Mexico mix design. An $8\frac{1}{2}$-in.-thick deck continuous for live load was made composite with the beams. The deck was built using 4000 psi cast-in-place concrete. The deck and integral diaphragms were placed at the same time.

Strand Congestion Alleviated

The beams contain 0.6-in.-diameter prestressing strands, which allowed fewer strands to be used. This approach reduced congestion, especially at the ends. U-beams do not accommodate strand harping easily because the webs slope at 1.5:1 vertical to horizontal and are wider at the top than the bottom. Discussions with staff at Rinker Materials (now Coreslab Structures) indicated that harping the strands for these beams presented difficulties, since the strand position relative to the web edge is not constant throughout the length of the harped section. A stress analysis indicated that the condition could also cause unwanted torsional stresses in the webs.

The other alternative was to debond strands at the ends of the beams. The increased bursting force, however, due to the larger diameter strands required special consideration. The solution was to add strands in the top flange and debond them in the midspan region. The debonded top strands were cut at the center after release and before beam erection. The timing of the cutting was decided by the supplier to assist with control of beam camber. The top strands also made placement of other reinforcing steel easier. The supplier now recommends the use of top strands in U-beams whether required by design or not.

The torsional stability of the U-beams eliminated the need for exterior diaphragms, making construction easier and enhancing the form of the bridge. Interior diaphragms were provided at third points along the length of the beam to prevent beam rotation. Solid interior diaphragms also were provided at the ends of the beams to accommodate the reinforcement required for the integral abutments and confinement for the anchorage zones.

Three-Point Bearing System Used

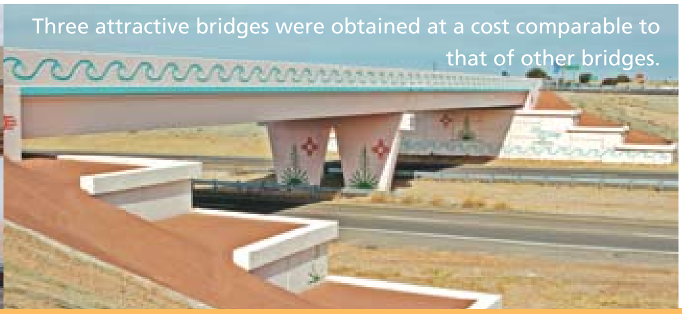
New Mexico has experienced several problems relating to bearing and torsional rigidity with both U-beams and large box girders. To address these issues, a three-point bearing system was designed for the U-beams. Two bearings per beam were placed at the pier and one bearing per beam was placed at each abutment. The arrangement allowed the beam to rotate on the single bearing and provided uniform bearing on the remaining two. Small, lightweight angles were added at a distance away from the bearings to retain the bearings if displacement occurs. To date, there has been no displacement and the bearings are performing well.

By grouping the three projects together, incredible time savings in construction were achieved. The three projects were completed in approximately one year. In addition to the time savings from working simultaneously on all three projects, the uniform design eliminated the learning curve on two of the bridges, reducing construction time for each activity. Producing similar beams also saved time in reconfiguring molds, jigs, etc.

The approach slabs used New Mexico's standard design, which consists of a 14-ft-long by 11-in.-thick slab that moves with the deck. The slabs are supported by the abutment on the bridge end and by a sleeper beam on the roadway end. Abutments are semi-integral with a short stub wall supported on spread footings. A diaphragm poured integrally with the deck is placed across the entire stub wall, developing integral movement between beam ends, deck, and approach slab. Elastomeric bearings are used to ensure uninhibited movement of the superstructure.

The wingwalls are also integral with the deck and diaphragm. To alleviate the problems of movement between the fixed stubwall and the movable wingwall, the stub wall was shortened on each end. The wingwalls were designed to be alongside the stubwall instead of behind it. Bituminous bond breakers were placed


U.S. 84 over I-40 in New Mexico uses precast U-beams with a cast-in-place deck.


Three attractive bridges were obtained at a cost comparable to that of other bridges.

BRIDGE TYPE: PRECAST, PRESTRESSED CONCRETE U-BEAMS / NEW MEXICO DEPARTMENT OF TRANSPORTATION, OWNER

BRIDGE DESCRIPTION: Three similar bridges consisting of precast, prestressed concrete U-beams and a continuous cast-in-place concrete deck

STRUCTURAL COMPONENTS: Four 54-in.-deep U-beams per span, MSE walls, abutments, and wing walls

BRIDGE CONSTRUCTION COST: $84 psf

between the wingwalls and the stub wall ends and footings. The design allows the wingwalls to slide back and forth freely beside the stub walls. The location of the wingwalls also locks the superstructure to the substructure transversely aiding in the elimination of sole plates.

Artwork Added

To fulfill the aesthetic requirements of welcoming visitors, 3D modeling with a basic rendering assisted with visualization of the completed form. Girders, piers, and MSE walls were designed to complement one another and provide an overall pleasing form.

Artwork was incorporated into the MSE walls, wingwalls, piers, and barrier curbs, using a technique of disposable foam or plastic of a given thickness to create recessions in the concrete. The recessed areas were painted in contrasting colors to the background. Recessed areas give definitive paint boundaries, which provide ease in initial and maintenance painting. The cost for forming and painting with this system was minimal with respect to the cost of other art systems.

The average unit costs for bridge structures on this project was $84 psf, slightly less than the average unit cost of $86 psf for all bridges in New Mexico that year. The cost effectiveness can be attributed to several factors, including simplicity and construction considerations in design; consultation during design with suppliers and contractors to develop easy-to-build and economical details; use of repetitive parts and materials throughout all three bridges; and a creative bid process that let contractors bid one bridge, any combination of two bridges, or all bridges on this project.

The New Mexico Department of Transportation was very pleased to get three attractive bridges at a cost that was comparable to that of other bridges. The careful planning and good communication throughout the design and construction process was responsible for the creation of three bridges that are aesthetically pleasing, structurally efficient, cost effective, and durable.

Joan D. Bowser, State Concrete Engineer (Former Bridge Engineer); Zann Jones, Bridge Engineer; Jimmy D. Camp, State Bridge Engineer; and Robert Meyers, State Materials Engineer are all with the New Mexico Department of Transportation.

Credit:
Portions of this article are based on a presentation at the 86th Annual Meeting of the Transportation Research Board (TRB), January 24, 2007, Washington, D.C., and accepted for publication in the 2007 series of the *Transportation Research Record: Journal of the Transportation Research Board*. Reprinted with permission of TRB.

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Kansas Standardizes

State officials liked the benefits of post-tensioned, haunched slab bridges and produced their own designs

by Stanley W. Woods

Reinforcing steel and post-tensioning ducts in a haunched slab bridge.

Department of Transportation officials in Kansas have become big believers in the use of concrete haunched slab bridges. The state has approximately 25,500 bridges, with about 5000 on state highways, and concrete haunched slab bridges comprise an extensive inventory in that number.

"These three-span structures work very well with the topography in Kansas, and our numerous stream crossings," explains Loren Risch, Bridge Design Engineer. The Kansas Department of Transportation (KDOT) previously had standards for reinforced concrete haunched slabs with center spans from 39 to 72 ft, using 4000 psi compressive strength concrete. As the center span length was limited to 72 ft, the design could only be used for shorter stream crossings. Subsequently, a consultant developed new standards for post-tensioned, haunched slab bridges that extended the span range to 92 ft in addition to providing a high performance bridge superstructure.

The longer spans fit very well with the wider stream crossings, says Risch. In creating these designs, KDOT followed the lead of Sedgwick County, one of their larger counties, which started using these bridges two years earlier. This was mentioned in the Spring 2007 issue of *ASPIRE.*™

Standard Plans Developed

The slab soffit features a parabolic profile with minimum depth at midspan and maximum depth at the pier. Longitudinal post-tensioning tendons are draped in a parabolic profile and provide the primary reinforcement to carry the loads. A nominal post-tensioning using straight tendons in the transverse direction is provided for distribution of loads and confinement. Nominal reinforcement is provided in both directions in the top and bottom of the slab for temperature and shrinkage stresses as well as to assist in the positioning of the post-tensioning ducts. Concrete design strength is 5000 psi.

Reinforcing steel and cable ducts just before the concrete placement.

The consultant developed standard plans to meet several different situations and to provide usable plans for the smaller counties. Four span arrangements are available in continuous three-span configurations of 50-65-50 ft, 55-72-55 ft, 62-82-62 ft, and 71-92-71 ft. Six roadway widths of 28, 32, 36, 40, 40 with an offset centerline for interstate bridges, and 44 ft.

The slabs are designed for a traffic barrier, a future wearing surface of 25 psf and HL-93 live load. These bridge standards all offer right-angle crossings. An example set of plans for a 30-degree skewed post-tensioned bridge is also available. "There have been some problems with the skewed bridges when careful attention was not given to the intersection of cable ducts and transverse reinforcing steel," explains Ken Hurst, State Bridge Engineer.

LEAP Software has produced a computer program for design and analysis of the slabs. The superstructure can be designed to satisfy current AASHTO Standard Specifications HS25 live load and the AASHTO LRFD Bridge Design Specifications HL-93 live load.

Design Used Statewide

These bridges are all let to contract, either by KDOT or one of the larger counties, and they are used statewide. One contractor has been the successful bidder in many cases. The state specifications require the post-tensioning contractor to be at the site at least three times during construction to oversee the contractors work when the ducts are placed, when the post-tensioning is applied, and when the ducts are grouted.

Kansas is very concerned about grouting the ducts and follows the American Segmental Bridge Institute (ASBI) specifications. Grouting must be done no more than 7 days after tensioning, using bagged grout placed by an ASBI certified contractor. So far, the state has built 11 of these bridge types with three more planned. Sedgwick County has built approximately 24 bridges.

Reinforced concrete haunched slab bridges cost between $65 and $75 psf, while the post-tensioned concrete haunched slab bridges cost between $75 and $85 psf. This slightly higher cost is expected with the longer span lengths. "The cost is slowly declining as contractors become more familiar with this method of construction," Hurst notes.

Other states have noticed the efficiencies. Iowa and Ohio officials have inquired about their use, and an Ohio developer has built at least one. Texas also inquired, but their typical bridge features flat slab concrete construction. The post-tensioning contractors also have inquired, Hurst adds, as they want to promote the design to bring them more business. "I am surprised this idea hasn't taken off a bit faster."

One design pushed the limit to a 102-ft center span and a depth-to-span ratio of 1:42. The bridge was built close to the ground and looks very good at the site, Hurst says.

The current standards for post-tensioned concrete haunched slabs are limited to three-span arrangements. Unlike the standards for the reinforced concrete haunched slabs, post-tensioned concrete slab designs cannot be extended to multi-span applications in a straightforward manner. The additional length of tendons results in an increased loss of prestressing force, which may require an increase in the initial force.

KDOT may in the future develop standards for multi-span applications. The maximum total length of post-tensioned concrete slab bridges, without introducing a strand splice or interior span joints, is expected to be about 600 ft.

The standards are available from KDOT in three components—Users Manual, Plan Standards, and Special Provisions. To learn more, visit www.ksdot.org

For more information on this or other projects, visit www.aspirebridge.org.

After the concrete has gained strength, the cables are post-tensioned and strand elongation measured.

The use of post-tensioning has extended span lengths up to 92 ft.

The design of the post-tensioned concrete, haunched slab bridge offers a graceful profile and slender appearance for the superstructure

Concrete Haunched Slabs

Integrating Research, Theory, and Practice into Building Concrete Bridges that Last

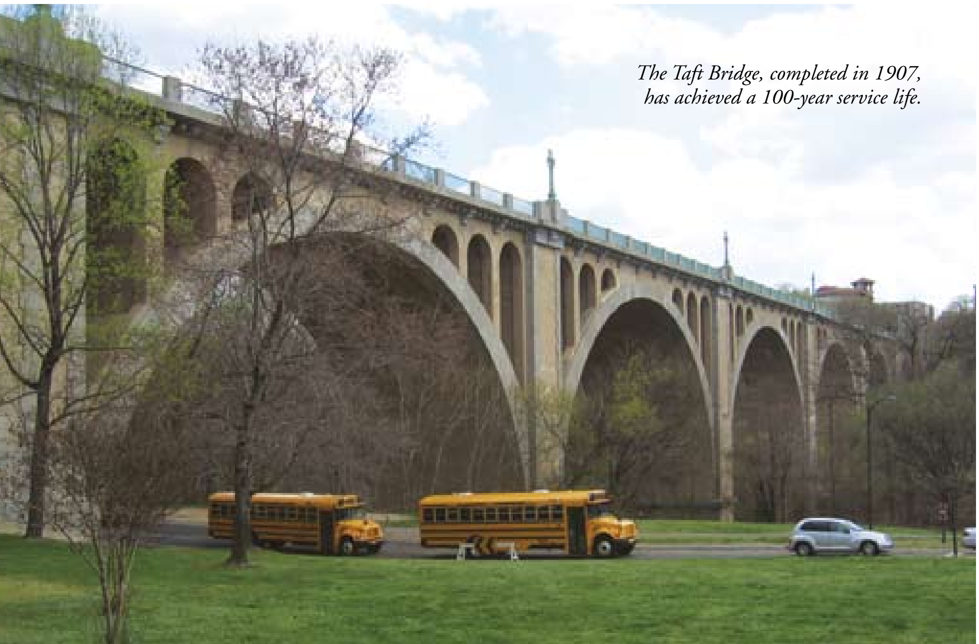
Concrete lions stand guard over the Taft Bridge.

by M. Myint Lwin

Concrete possesses some very desirable properties for the construction of bridges. Concrete is adaptable to a variety of shapes, forms, and colors, allowing engineers and architects to showcase their bold and imaginative expressions. Concrete has high compressive strength and resistance to environmental and chemical effects. It is relatively low cost, readily available, and easy to use in construction.

Cast-in-place concrete bridges can be made continuous and monolithic for improved durability, structural performance, and seismic resistance. Concrete is most suitable for superstructures with curved alignments and superelevations, piers with skews, ramps with various configurations, and structures with complex geometric forms and architectural features. Many concrete arch and tied-arch bridges built in the late 1800s and early 1900s are still in service. Some of them have undergone strengthening and rehabilitation to extend their service lives. One example is the Taft Bridge, which carries Connecticut Avenue over Rock Creek in Washington, D.C. It is an arch bridge with unreinforced concrete for the five arches and reinforced concrete for the deck. The large lion sculptures on the bridge were also made of concrete. The construction of the Taft Bridge started in 1897 and was completed in 1907. The bridge was renovated in 1990 and is expected to serve the communities for many more years.

Concrete is strong in compression but weak in tension. The true potentials of concrete were not realized until the industrial revolution in the 1800s, when structural steels were produced and readily available in large quantities and portland cement was produced in significant amounts in the United States. Ernest Ransome of California received a patent in 1884 for his invention of a twisted reinforcing steel bar. Ransome went on to design and build the first reinforced concrete bridge in the United States in 1884. The bridge is known as the Alvord Lake Bridge in Golden Gate Park, San Francisco, California. The bridge is still in service. The successful use of reinforced concrete in the Alvord Lake Bridge has led to the construction of many reinforced concrete arch bridges in other parks around the country. Robert Maillart and Eugene Freyssinet have been credited as the pioneers and champions in reinforced and prestressed concrete bridges, respectively. They set the trend for modern design and construction of cast-in-place, precast, and prestressed concrete bridges—arches, beams, box girders, segmental construction, and others. Precast and prestressed concrete members are often an integral part of modern cable-stayed and suspension bridges.



The Taft Bridge, completed in 1907, has achieved a 100-year service life.

The common goal of the FHWA bridge community is to work together with our state partners, industry, and academia to continuously improve the condition and durability of the nation's bridges and tunnels. Durability of bridges and tunnels may be considered as meeting the design life and serviceability requirements with minimal systematic preventive maintenance and low life-cycle costs. The design life, based on the AASHTO LRFD Bridge Design Specifications, is 75 years. For major bridges, the owners may specify that the bridges be designed and built for a design life of 100 years or more.

The AASHTO LRFD Specifications imposes four limit states to be satisfied by the design to achieve durability, serviceability, constructability, and safety. The limit states serve as a systematic approach to structural design to ensure low maintenance in the short- and long-term. The four limit states are:

Service Limit State: This limit state imposes restrictions on stress, deformation, and cracking under regular operating conditions.

Fatigue and Fracture Limit State: This limit state imposes restrictions on the stress range due to a design truck occurring at the number of expected stress cycles.

Strength Limit State: This limit state stipulates the strength and stability requirements to resist the specified statistically significant load combinations expected to be experienced by a bridge over its design life.

Extreme Event Limit State: This limit state ensures the structural survival of a bridge during events such as earthquakes, ice load, flood, scour, and vessel or vehicle collision.

The AASHTO LRFD Specifications fulfills a vision to design and build durable bridges for load effects with a high and uniform level of reliability.

The American Concrete Institute defines concrete durability as the ability of concrete to resist weathering action, chemical attack, abrasion, and other conditions of service. Specifically, concrete must be designed, proportioned, mixed, transported, placed, and cured properly to assure its resistance to potential freeze-thaw damage, alkali-silica reactivity, sulfate attack, chloride penetration, corrosion of reinforcing steel, abrasion, and load effects. The development of high-performance concrete (HPC) is aimed at achieving durable concrete.

Flexural test of ultra-high performance concrete beam. Photo courtesy of Ben Graybeal, FHWA.

The FHWA High-Performance Concrete Technology Delivery Team (TDT) has been created to work with the state DOTs in building more economical and durable bridges using high performance concrete. TDT members represent the FHWA, State DOTs, academia, and industry. The mission of the team is to improve the durability and cost-effectiveness of the nation's transportation infrastructure. The TDT transfers HPC technology to the states through workshops and showcases hosted by participating DOTs. The TDT maintains the "Community of Practice" website where users can post questions on HPC, participate in discussions, share documents, and review works in progress. The website address is http://knowledge.fhwa.dot.gov/cops/hpcx.nsf/home. The TDT has developed and published the HPC Structural Designers' Guide, intended to be a one-stop shopping reference for all aspects on the implementation of HPC. It is posted on the above website.

The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) establishes several research, deployment, and education programs for improving the durability and understanding the long-term performance of concrete bridges. These programs are:

The Long-Term Bridge Performance (LTBP) Program

This 20-year program involves detailed inspection and evaluation of the performance of a large section of the nation's bridges to (1) build a quantitative performance bridge database, (2) improve knowledge of bridge performance under all physical, chemical, and environmental conditions, (3) understand the deterioration mechanisms that affect durability of bridges, (4) improve inspection and condition information through nondestructive evaluation, and (5) develop emergency response, strengthening, repair, and retrofit procedures for rapid deployment following extreme events caused by natural and man-made hazards. This program is conducted by the FHWA in partnership with the states, consultants, industry, and academia. For more details of this program, visit http://www.tfhrc.gov/structur/ltbp.htm.

The Innovative Bridge Research and Deployment (IBRD) Program

This is a 4-year program for promoting, demonstrating, evaluating, and documenting the application of innovative designs, materials, and construction methods in the construction, repair, and rehabilitation of bridges and other highway structures. One component of the program is dedicated to research, deployment, and education of technology related to high performance concrete bridges. FHWA has developed the HPC plan in response to the needs identified by members of AASHTO, TRB committees, NCHRP, industry, academia, and others. Details of the HPC program are posted on the FHWA website. A major part of the IBRD program is to provide funds to the state and local highway agencies for incorporating innovations into construction projects for improved safety, reduced congestion, and greater durability. Annual solicitation of applications is issued for proposed projects that meet the goals of the program. FHWA will make its funding determinations through a merit-based selection process. For more details of this program, visit http://www.fhwa.dot.gov/bridge.

Ultra-high performance concrete, as used in this test bridge for FHWA, is a new material for bridge construction. Photo courtesy of Ben Graybeal, FHWA.

Highways for Life Pilot Program

The purpose of this program is to advance longer-lasting highways using innovative technologies and practices to accomplish the fast construction of efficient and safe highways and bridges. This program includes demonstration construction projects, technology transfer, technology partnerships, information dissemination, and monitoring and evaluation. HPC, including self-consolidating concrete and ultra-high performance concrete, has a definite place in this program in support of faster construction and longer-lasting structures. For more details of this program, visit http://www.fhwa.dot.gov/hfl.

The state-of-the-knowledge is such that we understand the factors that affect the durability of concrete, and we have the knowledge for preventive measures that must be taken to improve the durability of concrete for meeting the design life and serviceability requirements of a project. The key then is to integrate research, theory, and practice to assure quality workmanship in construction and defect-free bridges and tunnels that can withstand the test of time with minimal maintenance and low life-cycle costs.

U.S. Department of Transportation
Federal Highway Administration

Bridging Faults—California's Unique Engineering Challenges

by Raymond W. Wolfe and Michael D. Keever,
California Department of Transportation

Mission Valley Interchange, San Diego County (Multi-span box girders on single column bents).

The broad spectrum of landscape, from majestic mountain ranges to broad cultivated valleys and legendary coastline, defines the uniqueness of California. The state is situated at the junction of the Pacific and North American plates—two active tectonic crustal plates forming part of the "Rim of Fire." This is one of the most active volcanic and seismic regions in the world today. The constant shifting of the plates forms some of the most tantalizing landscape in the world, but also presents tremendous engineering challenges in one of the most heavily populated states. Geography, climate, and history have come together in California to produce dense population centers, with a high concentration of bridges in regions of high seismicity.

Adams Avenue Overcrossing, San Diego County (Three-span box girder bridge on pier columns).

Bridge designers in California face the somewhat unique challenge posed by the ever-present threat of earthquakes. A close inspection of fault maps reveals that the state is fragmented not unlike a textbook example of a shattered crystalline structure. Engineers and academicians continue studying earthquake damage and recorded seismic events to update design philosophies and details in an effort to mitigate damage. The basic underlying premise of bridge design in California is to prevent structural collapse. To ensure consistent behavior, the California Department of Transportation (Caltrans) has developed and continuously updates a seismic design manual—the Seismic Design Criteria (SDC). The SDC assumes that some structures or elements therein will require rehabilitation or replacement, but life preservation during the event is the primary consideration. However, California's most critical bridges have been designed to higher standards to provide some level of post-earthquake serviceability due to their importance in recovery activities and the economic impact of the closure.

The majority of bridge structures in California are cast-in-place, post-tensioned (CIP/PS) concrete box girders. The advantages afforded from precast construction are also realized in many instances, particularly when considering accelerated bridge construction. CIP/PS box girder structures have long held favor in California as they provide the following advantages:

- Monolithic connections, which are not susceptible to support loss due to ground motions;
- Excellent torsional resistance to seismic loading;
- Efficient designs for shear transfer and moment distribution;
- Historically, the most cost-effective structure type for many applications; and
- The preferred structure type of the local construction industry.

Ductile Design Detailing

Designing for purely elastic behavior in a seismic event is generally considered unnecessary as well-detailed concrete elements can resist loading through ductile response. Based on substantial research, Caltrans relies on ductile design detailing as a fundamental tenet of seismic bridge design. Ductile detailing in seismic zones is important because:

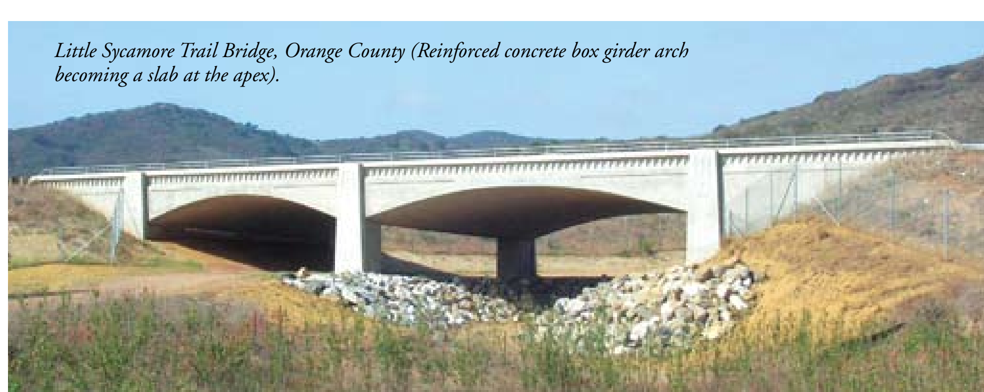
- It does not rely on highly accurate prediction of seismic demands;
- It ensures ductile response in predetermined plastic hinge zones resulting in an extended inelastic region with significant energy absorption;
- Ductility can be enhanced in a cost-effective manner through the addition of column confinement steel; and
- It yields a more cost effective foundation design by limiting the transmitted forces.

Elastic design produces stiffer bridges, which attract more seismic loads, increasing the cost of survivability and post-event serviceability.

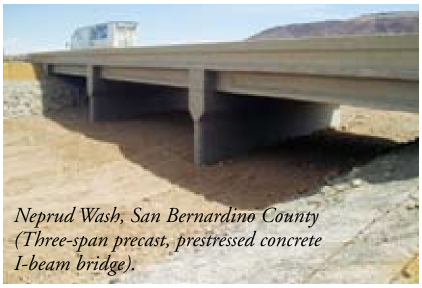
Substantial research in confined concrete sections has led to proven design details to limit damage and force plastic hinging to occur at predetermined locations in the columns. Poor detailing in columns leads to brittle failure. Caltrans design criteria establishes a minimum displacement ductility capacity of three. This ensures a level of post-elastic performance to address inherent seismic uncertainty, even in regions of low seismicity where seismic demands may not control the design.

Dynamic Design Considerations

Experience has highlighted the importance of balancing the overall structure to enhance its performance when subjected to seismic excitation. This is accomplished through providing a measure of "effective" stiffness



Little Sycamore Trail Bridge, Orange County (Reinforced concrete box girder arch becoming a slab at the apex).



Neprud Wash, San Bernardino County (Three-span precast, prestressed concrete I-beam bridge).

equity between adjacent bents in a frame and/or adjacent columns in a bent, and tuning the fundamental periods of vibration of adjacent frames. The above is analogous to an appealing aesthetic design wherein proportioning yields enhanced visual flow; seismic forces are better resisted through balanced geometries.

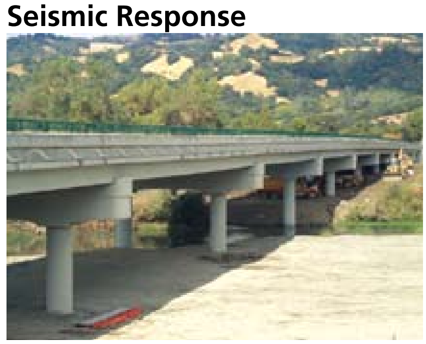
The concept of balanced "effective" column stiffness precludes the danger of substantial damage to stiffer elements from localized shear demand. An example of this is unbalanced inelastic response or increased column torsion demand due to rigid body rotation in the superstructure. Empirical data has led to target column "effective" stiffness ratios of $k_i^e / k_j^e \geq 0.75$, where k_i^e is defined as the smaller "effective" bent or column stiffness, and k_j^e is the larger bent or column stiffness. The calculated "effective" stiffness should consider column heights and diameters, framing effects, end conditions, longitudinal and transverse steel ratios, and foundation flexibility.

Long concrete bridges in California often incorporate in-span hinges to accommodate superstructure thermal movement without substantially increasing column stresses. Design of structures containing in-span hinges requires careful attention to the potential for out-of-phase response between adjacent frames. Neglecting this leads to increased probabilities of localized failure due to unintended collisions between adjacent elements excited by seismic events at different fundamental periods. Unseating of in-span hinges, an event leading to partial or total collapse mechanisms, was first identified after the 1971 San Fernando Earthquake. Modern designs incorporate a minimum hinge seat of 2 ft. Retrofit strategies for narrower seats primarily employ double extra-strong steel pipe seat extenders to accommodate larger longitudinal displacement excursions under extreme seismic events. Restrainer cables attached to concrete bolsters were employed in California's Phase I seismic retrofit program, with pipe seat extenders gaining favor later.

Another innovation developed to address this vulnerability is the "seatless" hinge. It consists of cantilever end spans, emanating from adjacent frames, butted together without restraint as in typical seated hinge configurations.

It is also important to limit the ratio of longitudinal and transverse fundamental periods of vibration between adjacent frames. Based on analytical studies, the SDC caps the ratio of the natural period of the less flexible frame to that of the more flexible frame at a minimum of 0.7. Effective strategies to accomplish this include adjusting "effective" column lengths, modifying end fixities, reducing/redistributing superstructure mass, modifying column reinforcement ratios, etc. Column length adjustments are typically the most easily incorporated, and involve simple footing depth modifications or isolation casings. The latter employs steel casings designed to provide a gap between the column and the surrounding soil mass to effectively lengthen the column.

Seismic Response



Russian River Bridge, Sonoma County (Precast, prestressed and post-tensioned double-tee superstructure used as an emergency replacement).

Modification Devices

Isolation from extreme event forces such as earthquakes is a proven means of cost-efficient design. This strategy has been employed in civil infrastructure design worldwide, from Japan to Italy and California. Rather than relying solely on ductile behavior, the premise is to limit the forces transmitted into the structure by isolating portions from ground motions, or reducing the input magnitude. Numerous devices exist today to accomplish this goal, from large self-centering bearings to viscous dampers, hysteretic damping mechanisms, and lock-up devices. These are particularly useful when considering retrofitting existing structures not previously detailed to respond in a ductile fashion to large displacement demands. As primary reinforcement confinement is crucial to ductile behavior, it may be difficult to incorporate into existing structures, particularly on large-scale structures, and thus isolation strategies become more enticing for retrofits. Most of the major long-span toll structures have some type of seismic response modification device to enhance performance and limit damage. However, because of their cost and long-term maintenance needs, these devices are not typically used on "standard" structures designed with today's criteria, or those that can be retrofitted with simpler solutions.

Donner Park Overcrossing, Nevada County (Two-span cast-in-place post-tensioned box girder).

Future Innovation

Accelerated bridge construction has received much attention in recent years, largely through a concerted effort by the Federal Highway Administration and public demand for less interruption from highway construction projects. Research projects contemplating substantial diversions from historical design norms such as re-centering precast column/bent elements may prove viable for future bridges. The long-term vision for transportation projects across the Golden State includes incorporation of design features leading to rapid on-site construction. Increased structure durability and enhanced post-earthquake serviceability must be provided to effectively meet the motoring public's demands, maintain California's prominence in the global economy, and promote good environmental stewardship.

Conclusion

California has and continues to expend tremendous resources developing design criteria and pursuing research in an effort to counter seismic effects on bridges. The SDC is performance-based. In simple terms, the element and system capacities are selected to exceed the imposed demands. The strong beam-weak column approach focuses the damage at predefined locations, otherwise known as plastic hinge zones, in column elements. System redundancy is required to provide alternate load paths and prevent local failure from resulting in collapse. Targeting a minimum ductility prevents brittle failure modes, which are often sudden and catastrophic. Some solutions employ seismic response modification devices to isolate or limit exciting forces from specific areas of structures. The goal is to prevent collapse, while localizing damage to accommodate repairs.

Hamilton County, Ohio, uses high performance concrete to reduce chloride penetration, minimize deck cracking, and provide 75-year service life.

Spread Box Beams Provide Economic Solution

by Stephen J. Mary and Matt Yunger, Hamilton County, Ohio

Willey Road Bridge in Hamilton County received the 1998 PCI Bridge Design Award for the Best Rehabilitated Bridge.

The Bridge Department of Hamilton County, Ohio, is responsible for the inspection and maintenance of 521 bridges on the county road system—mainly in the greater Cincinnati area. The department strives to preserve historic structures whenever possible and has received three awards in "Recognition of Outstanding Efforts in the Rehabilitation of Historic Structures" from the Ohio Department of Transportation.

By state law, each bridge structure must be inspected annually. Bridges determined to be structurally or functionally obsolete are included in the Capital Improvement Plan for rehabilitation or replacement. This article describes the replacement of one of our bridges using high performance concrete (HPC).

As the Hamilton County Engineer's Office (HCE) anticipated replacement of the Zion Hill Bridge, which had a prestressed concrete box beam superstructure on older concrete and stone abutments, there were several considerations to be addressed. The goals for this project included improvement of the approach geometry, installation of a new water main on the superstructure, a bridge service life of 75 years, and a cost-effective structure.

Spread box beams provide an economical solution for the new Zion Hill Bridge.

The water main was located between, and protected by, the spread box beams.

To minimize stream disturbance and environmental impacts, the existing massive stone and concrete rear abutment would remain in place as a retaining wall.

Many county bridges in Ohio, including those in Hamilton County, use adjacent box beams with an asphalt wearing surface. For this project, adjacent box beams could not accommodate the deck overhang required to improve the roadway geometry. The HCE in conjunction with the engineering firm of Parsons Brinckerhoff, Inc. determined that a bridge using spread box beams (48 in. wide by 39 in. deep) with an 8-in.-thick cast-in-place reinforced concrete deck could be designed with a substantial deck overhang to flatten the curve at the rear abutment. The overhang varied from 2 ft near midspan to 7 ft close to the rear abutment. The HPC deck was made composite with the box beams.

The use of spread box beams, with a 7-ft 10-in. center-to-center spacing reduced the project cost by eliminating half the number of box beams needing to be fabricated and shipped to the jobsite. The 3-ft 10-in. clear span between the beams allowed the 16-in.-diameter water main plus insulation and casing to be placed between the box beams. In comparing the usual adjacent beam design to the spread beam design, it was determined that the costs of the reinforced concrete deck necessary with the spread beam design were less than the additional costs for the extra beams in the adjacent beam design.

The specifications for the box beams, supplied by Prestress Services Industries of Melbourne, Kentucky, included the use of silica fume in the concrete and epoxy-coated reinforcement. Inserts were installed in the sides of the beams for water main hangers and the concrete diaphragms. Inserts were also installed in the top edges of the beams to facilitate deck forming. Concrete compressive strengths at 1 day averaged 7400 psi, while preshipping strengths averaged 9100 psi for the four prestressed concrete box beams.

The specifications for the HPC in the deck included a maximum water-cementitious materials ratio of 0.40, maximum slump of 6 in., minimum compressive strength of 4500 psi at 28 days, silica fume admixture at 7 percent by weight of cement, Cortec MCI-2005NS migrating corrosion inhibitor, and 2 pcy polypropylene fibers with 3/4-in. minimum length. The blending of aggregates for a uniform gradation was also required. The contractor—Tri-State Concrete Construction of Cincinnati, Ohio—and the concrete supplier—Harrison Concrete of Harrison, Ohio—were encouraged to minimize the cement content to help reduce the potential for plastic shrinkage cracks. Once the mix design was submitted by the supplier and approved by the bridge department, a test slab was completed to ensure the air content, compressive strength, and workability of the concrete mix.

Deck curing consisted of the application of a curing compound as soon as the finishing process was complete. A wet burlap cure with continuous soaking for 7 days was also required as soon as practical without marring the surface.

Hamilton County has been using HPC mix designs with great success. Approximately 90,000 ft^2 of reinforced concrete deck as part of 11 different bridge projects has been placed successfully with minimal or no deck cracking. Hamilton County believes that high quality concrete begins with a good mix design, which includes maximizing aggregate sizes by blending, protecting the reinforcing steel, and reducing water and paste in the mix. A dense and crack-free concrete slab is the goal. The use of chemical admixtures that compensate for reduced water content, fibers to control plastic shrinkage cracking, good curing practices, and sealers, where appropriate, all contribute to achieving a 75-year service life.

Stephen J. Mary, Bridge Engineer and Matt Yunger are both with Hamilton County Bridge Department, Ohio.

American Coal Ash Association

The American Coal Ash Association (ACAA) advances the management and use of coal combustion products (CCPs). Generically, CCPs are the residuals from coal combustion, such as fly ash, bottom ash, and boiler slag, or byproducts from air emission controls. In addition to a myriad of core performance attributes in construction and industry, CCP use can conserve natural resources, reduce greenhouse gas emissions, and eliminate the need for additional landfill space. Nearly 40 percent of 123 million tons of CCPs produced annually are used beneficially.

Members of ACAA are located worldwide and include utility and non-utility CCP producers, as well as marketers, organizations, and individuals with commercial, academic, research, and other interests in CCP management. Members promote CCP use and management in ways that are environmentally responsible, technically sound, and commercially competitive. This mission is achieved through public and private sector partnerships, technical assistance, education, publications, meetings, and workshops. ACAA has developed strong partnerships with the Federal Highway Administration, Environmental Protection Agency, Department of Energy, Department of Agriculture, and others. Through these partnerships, the association helps provide information, education, and outreach to engineers, designers, specifiers, end users, and regulatory agencies.

Fly ash and cenospheres are CCPs often specified for high performance concrete in bridge decks, piers, and footings. The recently completed $531 million Arthur B. Ravenel Jr. Bridge project in Charleston, South Carolina, used more than 30,000 tons of fly ash. Caltrans, a state leader in the use of fly ash in paving projects, specified high volume fly ash mixes for the largest bridge project in its history—the San Francisco-Oakland Bay Bridge. Using innovative specifications and blending techniques, Caltrans was able to improve the workability, permeability, and hardened concrete properties. A number of engineering standards and specifications define CCP applications, thus ensuring high quality performance and products.

For more information, please visit www.acaa-usa.org.

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For more information on WRI or WWR, visit www.wirereinforcementinstitute.org or call 800-552-4WRI [4974].

2007 Interim Changes

by Dr. Dennis R. Mertz

The fourth edition of the AASHTO *LRFD Bridge Design Specifications* was published at the beginning of this year. This 2007 edition incorporates all of the interim changes since the publication of the third edition in 2004, and the new items approved by the AASHTO Subcommittee on Bridges and Structures (SCOBS) at their Annual Meeting in 2006. The items are identified as Agenda Items 8 through 15A and are reviewed in this article and will continue in the next edition of *ASPIRE.*™

Agenda Item 8 includes revisions to LRFD Article 5.10.11.4.1 relating to seismic performance of concrete bridges in Seismic Zones 3 and 4. The term "seismic hoop" is defined as a noncontinuously wound tie with a closure made using a butt weld or mechanical-closure coupler as a potentially superior alternative to spirals and to distinguish these seismic hoops from traditional AASHTO-defined hoops. Further, these revisions no longer permit lap splices anywhere in longitudinal column reinforcement in Seismic Zones 3 and 4. Commentary is added about the advantages of seismic hoops over spirals and the rationale for eliminating lap splices in these columns.

Fatigue stress range limits for welded wire reinforcement are added to the limits for reinforcing bars in Article 5.5.3.2 through Agenda Item 9. An adaptation of the traditional equation for fatigue stress range limits is extended to welded wire reinforcement without a cross weld in the high-stress region, while a new more restrictive equation is presented for welded wire reinforcement with a cross weld in the high-stress region. Both equations eliminate the current (r/h) term for deformed reinforcement by substituting the suggested value of 0.3, which has been almost universally assumed in practice.

Perhaps, the most significant change for concrete bridges is the addition of a simplified procedure for shear resistance using the modified compression field theory (MCFT) approach of the *LRFD Specifications*. Agenda Item 10 adds a more traditional approach for the shear resistance of concrete members, wherein the lesser of V_{ci} and V_{cw} comprises the concrete contribution to shear resistance instead of the iterative approach of the MCFT model. This new simplified model is analogous to the shear resistance model of the AASHTO *Standard Specifications for Highway Bridges*. While simpler to apply, the new alternative shear-resistance model can also be relatively conservative.

The most significant change is the addition of a simplified procedure for shear resistance.

In the 2006 Interim Revisions, the equations for the determination of shrinkage and temperature reinforcement of LRFD Article 5.10.8 were modified. Agenda Item 11 provides additional clarification in this article for the maximum shrinkage and temperature reinforcement spacing and for situations where this reinforcement is not required due to thinness of the component.

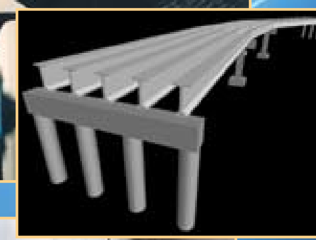
Changes were also made in 2006 Interim Revisions to the manner in which resistance factors, ϕ, for prestressed and nonprestressed members are determined. Instead of determining the resistance factor based upon the type of loading, ϕ is now determined by the strain condition at a cross section at nominal resistance. Consequently, the linear variation of ϕ between axial load levels of 0.0 and $0.10f'_cA_g$ is no longer applicable. Agenda Item 12 removed it from Fig. C5.10.11.4.1b-1. The proposed change requires that ϕ for the cross section at nominal flexural resistance with zero axial load be calculated to establish the starting point for the interpolation of ϕ for column design in Seismic Zones 3 and 4. This is consistent with the changes made in 2006, since reduced ductility is compensated by increased over-strength (i.e., a reduced ϕ factor). The change also provides for the potential use of prestressed concrete columns.

Agenda Item 13, which updates LRFD Article 5.14.1.4, provides extensive revisions to the specification and commentary for bridges composed of simple span, precast girders made continuous. These revisions are based upon the latest research findings as reflected in National Cooperative Highway Research Program Report 519.

Agenda Items 14 through 15A relating to concrete bridges from the 2006 AASHTO SCOBS meeting will be reviewed in the next issue.

A Passion for Engineering

Eriksson Technologies was founded in 1998 with a singular objective: the passionate pursuit of technical excellence. This philosophy is evident in every aspect of our company, from our highly acclaimed technical support down to the smallest technical details of our software. It's what has made us the preferred provider of engineering software to many DOTs, consulting engineers, precast fabricators, and universities nationwide.



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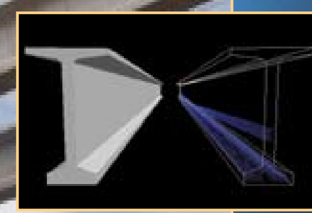

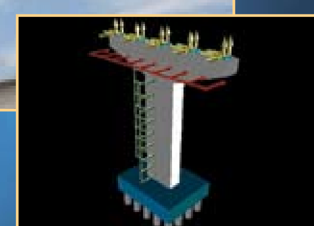

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Erikkson understands bridge engineering. We stay abreast of proposed specifications changes and new design methodologies through our active involvement in industry committees and our participation in cutting-edge research.

Our typical role on a research team is to serve as the vital link between pure research and engineering practice, which gives us special insight into the behavior of bridges. Better understanding of the underlying theory gives us a strategic edge in developing better modeling tools.

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Through our technical seminars, we have trained hundreds of practicing engineers to successfully make the transition to LRFD and helped them stay current with yearly changes in the specifications.

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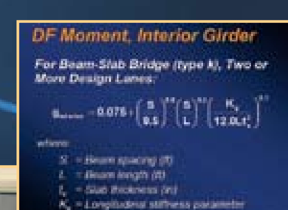

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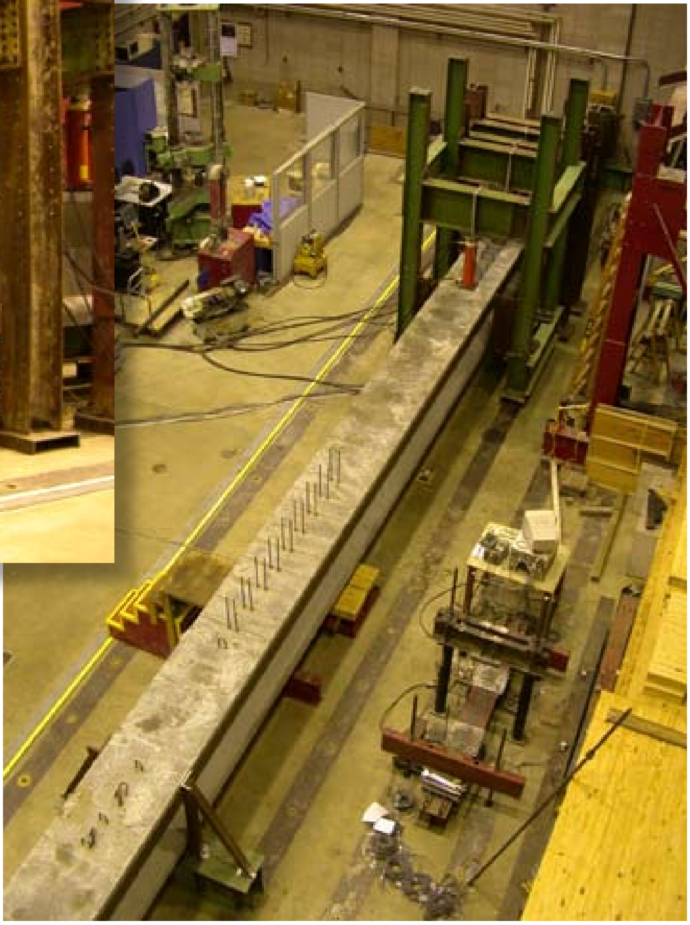
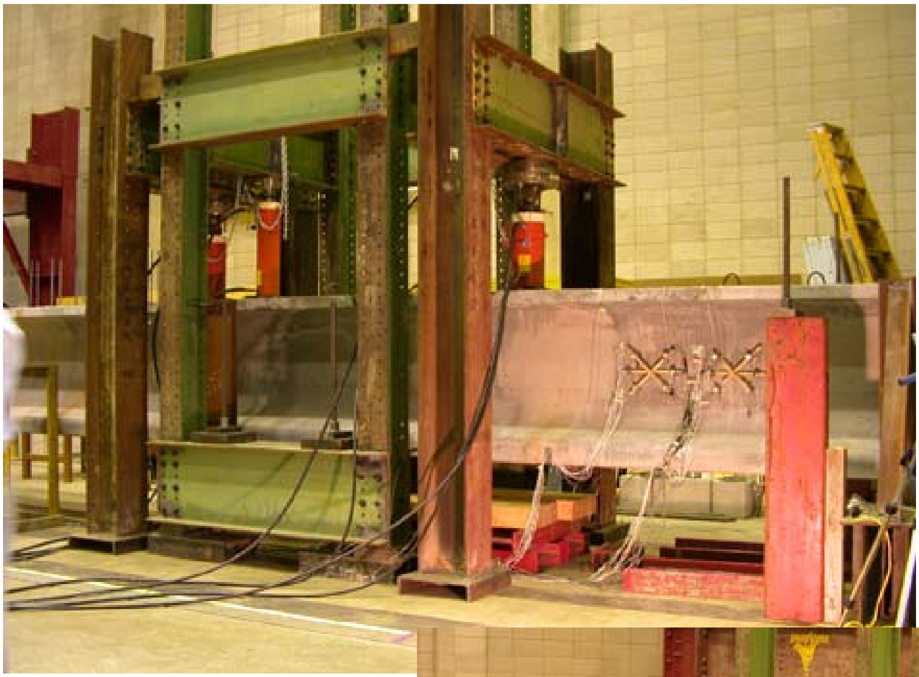


Load Testing



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