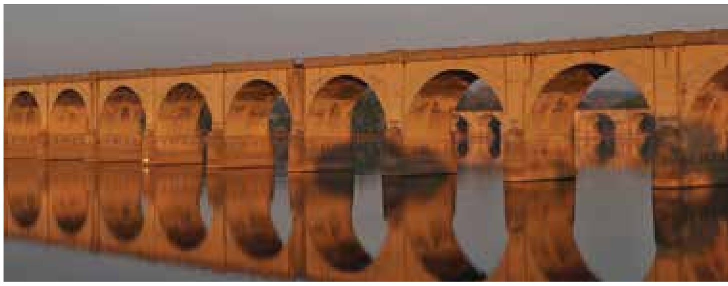
Pittsburgh
ENGINEER
SUMMER 2017
Quarterly Publication of the Engineers' Society of Western Pennsylvania

ARCH BRIDGES
NATURAL & MAN-MADE



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ESWP 1880 ENGINEERS' SOCIETY of WESTERN PENNSYLVANIA

In this Issue...

About the Cover...

Depicted on the cover are the "Top 10" photos from the 6th Annual IBC Photo Contest. For indentification and photo credits, please view the full article starting on page 31. Thanks to all of those who submitted photos for this year's contest!

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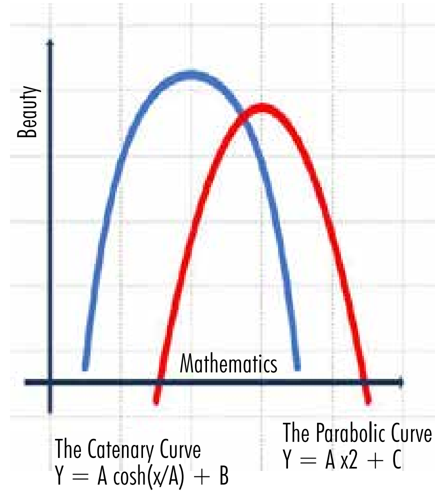


THE ARCH

- at the Intersection of Mathematics and Beauty

Does any other fragment present a feat of structural engineering with such seemingly effortless grace? *Leah Sinclair, 2014*

Who is not inspired by the form of the arch – be it created by nature or constructed by man? Who has not asked the question: How does such a slender form defy gravity and support such enormous weight with effortless grace? Throughout history, the arch has served two purposes – the first being to efficiently span a large distance – and the second being to reflect a monumental form of repetition and delight. While the origin of the arch is uncertain, many ancient cultures utilized its form, from the Mesopotamians constructing the simplest of structures, to the Chinese celebrating beauty and form, to the Romans celebrating victories and constructing large scale civilian works, to the medieval masons supporting their inspiring Gothic masterworks, and to our present bridge community combining efficiency and beauty in structural engineering. The arch's seductive form transcends time and cultures and has led to many of nature and man's most awe-inspiring creations.

But just what is an arch – is it as da Vinci said: "… two weaknesses which, leaning against the other, make a strength?" What defines its shape? Is it a simple mathematical statement or does it involve mathematics of complexity? What accounts for its beauty?

THE CATENARY

"I have lately received from Italy a treatise on the equilibrium of arches, by the Abbé Mascheroni. It appears to be a very scientifical work. I have not yet had time to engage in it; but I find that the conclusions of his demonstrations are, that every part of the catenary is in perfect equilibrium. It is a great point in a new experiment, to adopt the sole arch, where the pressure will be borne by every part of it." from a letter written by Thomas Jefferson to Thomas Paine, on December 23, 1788 from Paris, France.

Not realizing it at the time, Thomas Jefferson coined the term "catenary" – the true mathematical expression for the shape of an arch, which bears its own weight so efficiently that each element, along a line perpendicular to its axis, lies in uniform compression. While scant archeological evidence points to the Mesopotamians, who used a brick arch in rudimentary form some 4,000 years ago, it was not until the advent of calculus that a secret of nature was revealed. The secret: the true shape of the most efficient structural form to support self-weight is the hyperbolic cosine – the catenary or a mathematical curve based on the natural exponential function (e^x).

The Delicate Arch, Arches National Park, Utah
Photo courtesy of the National Park Service

Nature itself abounds with evidence of this solution, as a trip to several of the National Parks in the US west will attest. Artisans of the Renaissance through modern times with no formal mathematical understanding but with a strong empirical sense of order, recognized that the inverse of a draped chain provided the exact blue print for the "true" shape of an arch. These artisans used this technique to perfection to construct such magnificent structures as the ceiling of the King's College Chapel, Cambridge, UK (built over a period of a hundred years from 1446–1531).

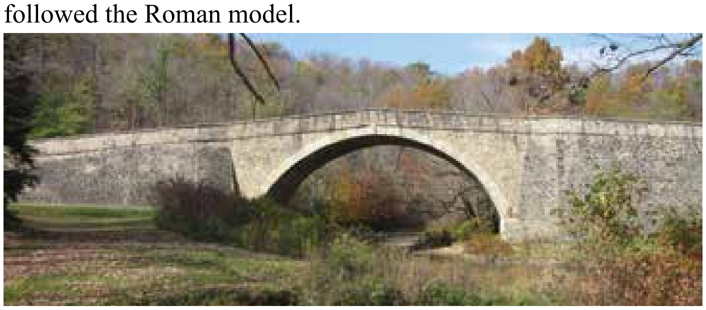
THE SEMI-CIRCULAR ARCH & THE ROMANS

"Architecture depends on Order…Order gives due measure to the members of a work considered separately, and symmetrical agreement to the proportions of the whole…There is also a kind of powder which from natural causes produces astonishing results. It is found…in the country belonging to the towns round about Mt. Vesuvius. This substance, when mixed with lime and rubble, not only lends strength to buildings of other kinds…let the masonry [of the aqueduct] be as solid as possible, and…let the masonry structure be arched over, so that the sun may not strike the water at all…", Ten Books on Architecture by Viitruvius, Books I, II & VII, c. 15-30 BC.

Roman bridge of Córdoba over the Guadalquivir River, a first century Roman bridge, rebuilt by the Moors in the 8th century and rehabilitated in 2006.

Photo Courtesy of Jim Dwyer.

The earliest surviving book on Roman architecture (by Vitruvius dedicated to his patron, Caesar Augustus) outlined the fundamentals of Roman thought and discovery which resulted ultimately in significant and long lasting monumental arched structures. What we may call structural engineering was viewed by the Romans as a combination of architecture and construction, founded on the mathematics of repeated, symmetrical, orderly geometric forms, the application of simple construction principles, and reliance on an abundant supply of raw materials and a cheap labor force. From the Roman point of view, an arch structure of any size would "work" as long as the proportions were appropriately scaled. In addition, the important discovery of manufactured cement, supplied by an abundance of nearby naturally occurring materials, facilitated the vision that any arch structure, be it a bridge, viaduct or aqueduct, of any size could be constructed. For the past 2,000 years, architecture has been inspired by this classical tradition. The resulting construction of arched masonry structures for bridges has followed the Roman model.



Little Crossings Bridge, National Road (US 40) spanning the Casselman River, Casselman State Park, Grantsville, MD. Photo courtesy of the Editors.

We have constructed] "the largest and we think the most permanent stone arch in the United States." November 16, 1814, Recollected in Historical Architectural and Engineering Record (HAER).

THE PARABOLIC ARCH

By the early 1800's, materials with high strength to weight ratios began to systematically replace masonry as a backbone structure support. Examples included the "reinforcing" of the trussed elements of covered bridges with wooden arches to eliminate observable deflections. The construction tradesman at the time did not realize the basic physics of their construction: the arches were not simply "reinforcements" but were the principle load carrying members of the structural system. With advances in the understanding of engineering mechanics and new and exciting construction materials available in the 19th century, the weight of the arch, then constructed with cast iron, wrought iron and steel, became a very minor contributor to its load carrying capacity. A new structural form was needed. The new form, the parabola, is a pattern that repeats itself many times over in nature. Consider a wind-swept sand dune that experiences strong unidirectional winds. The resulting landscape reveals multiple ridges of arcing, parabolically profiled, dunes. Similarly, when the weight of the structure and live loads are principally equal and unidirectional, the parabola, with its noticeably sharply curved apex, becomes the most structurally efficient form to convey load. To reinterpret the 1788 observation of Thomas Jefferson: "… every part of the [parabola] is in perfect equilibrium."

Perhaps the parabola has become the most appealing architectural form. Why is this? Is it because the parabola is the shape of a projectile in motion, the spray of a garden hose or the path of a waterfall? Is it because of its mirror-imaged shape and its uniformly varying profile with distance? Is it because, when positioned at the focal point, directional light and sound waves are amplified? It is the beauty of the symmetry of the double image when an arch is reflected on a calm water surface? Is it because when an arch is viewed at one position, it is symmetrical and logical and when viewed at another position, it becomes complex and undefinable?

Perhaps Frank Lloyd Wright, the father of organic architecture, and considered by some the "best American architect of all time", said it best when he said "I'll bridge these hills with graceful arches:"

Viaduct over the Alamonte River, Caceres, Spain

IBC 2017 Lindenthal Award Winner

Photo Courtesy of ADIF Alta Velocidad

"An arch consists of two weaknesses which, leaning against the other, make a strength." Leonardo da Vinci.

Welcome to the special summer edition of the Pittsburgh Engineer, devoted entirely to arch bridges – both natural and man-made. Enjoy our many articles on arch bridges and enjoy the splendid photography in our 6th annual photo contest, featuring natural and man-made arches from around the world. We hope you like arches – we do!

The Guest Editors

Chairman's Welcome

By Matt Bunner

On behalf of the Engineers' Society of Western Pennsylvania (ESWP) and the IBC Executive Committee, welcome to the 34th Annual International Bridge Conference! This year we return to our Nation's Capital and to the wonderful facilities provided at the Gaylord National Resort and Convention Center. Last year was our first year hosting in the D.C. area. This followed over three decades of the ESWP hosting the Conference in Pittsburgh.

Last year we felt a new sense of interest and enthusiasm from our attendees and exhibitors. Making the monumental move from Pittsburgh was a challenge for many of us on the Executive Committee who have roots in the City of Bridges. However, we found the new site in National Harbor a welcoming venue with many benefits and enhancements that helped make the 33rd Conference successful and memorable. We look forward to continued growth and success this year for the IBC, the pre-eminent international technical bridge conference and exhibition.

This year we are honored to welcome, from just a few miles away, the District Department of Transportation (DDOT) as our Featured Agency. DDOT manages and maintains the transportation infrastructure for the District of Columbia. On Monday June 5th, DDOT will host a Featured Agency Session that will provide an overview of their bridge program, a discussion of their historic structures, and focused presentations on an interesting and varied collection of their bridge projects. DDOT will also host a special area on our exhibit floor. We invite you to stop by and learn more about DDOT and their bridge program.

Our Conference is once again blessed with so many outstanding technical presentations that we are starting our Technical Sessions bright and early in the morning on Monday, June 5th. Later that same morning, our Keynote Session will signal the official start of the Conference. This year we are excited to be joined by Mr. Leif Dormsjo, Director of DDOT. In addition, Mr. Joseph Abriatis, who works for the Architect of the Capitol and was the construction manager for the U.S. Capitol dome restoration project, and Mr. Scott Jarvis, who is Chief Engineer for the California High Speed Rail Authority will be presenting on their landmark projects. Additionally, US Transportation Secretary Elaine Chao has been invited as our keynote speaker. We look forward to her insight into the new administration's plans for major infrastructure investments which will help repair our existing infrastructure and fund new transportation projects.

The IBC Executive Committee has always felt that the cornerstone of our Conference is our technical program that is second-to-none, something that attendees have come to expect at the IBC. This year will not disappoint as we have received and reviewed more abstracts than ever before from across the country and around the world. We have worked diligently to select an outstanding group of nearly 110 presentations and 13 workshops that will fill the four days of the IBC with valuable information that will benefit you immeasurably in your future work.

Matt Bunner

A new highlight on the afternoon of Tuesday, June 6th, will be a Boat Tour presented in conjunction with DDOT. Those attending will be picked up in National Harbor and will cruise the Potomac and Anacostia Rivers for the afternoon, viewing the bridges and other monuments along the way. DDOT representatives will be on hand providing narration along the tour route. You will arrive back at National Harbor late in the afternoon in time for Tuesday night's Awards Dinner. Our Awards Committee has reviewed many outstanding nominations this year and selected a most-impressive group of winners. This includes Mr. Vijay Chandra, winner of the John J. Roebling Lifetime Achievement Award. Mr. Chandra served as a Senior Bridge Technical Manager for Parsons Brinckerhoff and guided the design of numerous signature bridge projects over his many years of service to our profession. Seating is limited and a separate registration fee is required for both the Tour and the Awards Dinner, so be sure to sign-up early.

Building on the incredibly strong response from exhibitors last year, we expect over 150 booths this year in our Exhibit Hall, which will provide an excellent venue to network with others from across the bridge community. Our Exhibit Hall will host lunches on Monday through Wednesday, an evening reception on Monday, and a new breakfast event on Wednesday morning. The format will once again enable our exhibitors to attend our technical sessions.

Please join me in thanking the volunteer Executive Committee members, as well as the ESWP Staff, who have worked diligently over the past year to organize an outstanding program of technical presentations, workshops, exhibits and special events highlighting recent developments, current trends and state-of-the-art practices in the bridge industry. The Committee's goal is to provide this exciting program in a comfortable and enjoyable atmosphere. When you see Committee members throughout the week, please provide feedback to them on your experience and ways you feel that we can improve the Conference. We hope you have a rewarding experience this year and will return again in 2018 for the 35th anniversary Conference where we will feature the People's Republic of China.

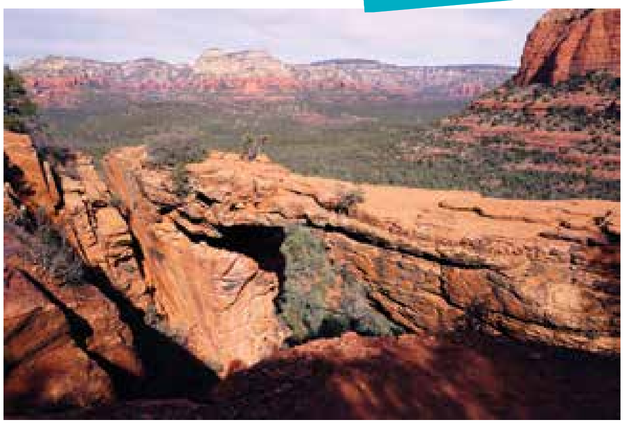
We are so happy that you have joined us for this year's IBC!

Matt

Matt Bunner, PE, is the General Chair of the 2017 International Bridge Conference and a Vice President and Senior Professional Associate for HDR.

Bridge Quiz

– Natural and Man-Made Arches



A. Can you name this natural bridge and its location in this stunning landscape?
Photo Courtesy of Jonathan McHugh

B. Can you name this man-made bridge and its location?
Photo Courtesy of Jim Radion

C. Can you name this natural bridge and its location in this stunning landscape?
Photo Courtesy of Warren Kaplan

D. Can you name this man-made bridge and its location?
Photo Courtesy of Adam Marolf

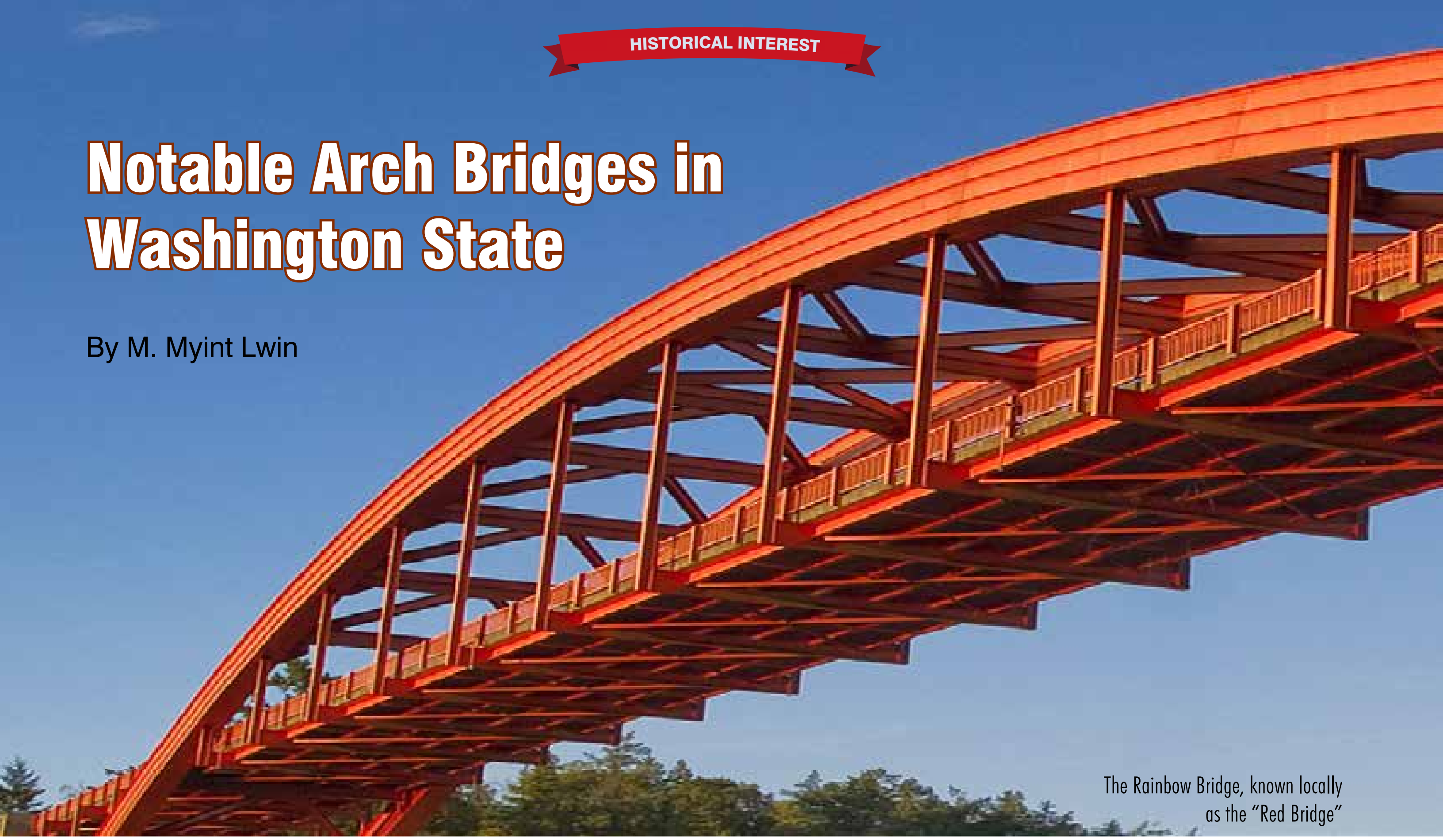
E. Can you name this man-made bridge and its location in this stunning landscape?
Photo Courtesy of Maxim Nasab

F. Can you name this man-made bridge and its location?
Photo Courtesy of Maxim Nasab

ANSWERS TO THE BRIDGE QUIZ CAN BE FOUND AT THE CONCLUSION OF THE FOLLOWING ARTICLE

Notable Arch Bridges in Washington State

By M. Myint Lwin



The Rainbow Bridge, known locally as the "Red Bridge"

WASHINGTON STATE has a rich history and culture in building safe, durable, efficient, economical and attractive vehicular and pedestrian bridges, including arch bridges of different types. In this article, I will introduce to the readers a sampling of notable arch bridges in Washington State with brief descriptions and pictures. More information on these and other arch bridges in Washington State may be found in the references given at the end of the article.

According to American Forklore, a natural rock-arch bridge once spanned the Columbia River between Washington State and Oregon State. The Natives called this bridge "Bridge of the Gods". The bridge was said to have fallen in 1775. The fallen rocks caused the river to rise to a height such that salmon could jump a fall in the river to return to spawning grounds. To commemorate the legend, a toll bridge named "The Bridge of the Gods" now exists near by the legendary "Bridge of the Gods"!

Historic and modern arch bridge building might be traced back to the discovery of the "True Arch" thousands of years ago. The ancient builders found that by putting the sun-baked bricks on ends, the arch ring stayed in place. (This is the structural principle of the voussoir arch and vault.) This was an important discovery that led to beautiful architecture of cathedrals, domes, buildings and bridges. This might very well be the beginning of ancient and modern arch bridge design and construction!

Trent Avenue Bridge

The Trent Avenue Bridge is a five-span concrete closed spandrel deck arch bridge over the Spokane River, located on SR290 in the City of Spokane, Spokane County. The bridge was constructed in 1910 with the following dimensions:

TOTAL LENGTH: 513' | MAIN SPAN: 100' | ROADWAY WIDTH: 40'

This is also known as a Luten arch bridge named after Daniel B. Luten (1869-1946), a bridge builder, engineer and good businessman. He designed and patented the Luten arch. His design used reinforcement to resist tension in concrete to lighten the structure, and filled the spandrel barrel with earth to form the base for the roadway. He obtained more than 30 patents on the different variations of the Luten arch design. By 1919 he had designed and built more than 17,000 Luten arch bridges across the U.S., many of which were built in Washington State.

Selah Creek Bridge

The Selah Creek Bridge, also known as the Fred G. Redmon Bridge, is a twin concrete open spandrel arch over Selah Creek on SR82 near Ponoma, Yakima County. The bridges were constructed in 1971 with the following dimensions:

TOTAL LENGTH: 1,337' | MAIN SPAN: 550' | ROADWAY WIDTH: 38' | RISE ABOVE CANYON FLOOR: 325'

Fred G. Redmon was an original member and first Chairman of the Highway Commission formed in 1951 to oversee the Washington State Department of Highways. At the time the bridge was built, it was the highest bridge in the State of Washington and the longest in the U.S.

Baker River Bridge

The Baker River Bridge is a reinforced concrete open spandrel arch over the Baker River, located on SR20 in the City of Concrete, Skagit County. The bridge was named "Henry Thompson Bridge" in honor of Henry Thompson, who was Chairman of the County Board of Commissioners responsible for raising funds for building the bridge. The bridge was constructed in 1917 with the following dimensions:

TOTAL LENGTH: 269' | MAIN SPAN: 196' | ROADWAY WIDTH: 18' + 5' SIDEWALK

The bridge is an early example of a reinforced-concrete open spandrel arch and was considered as one of the longest single-span concrete structures in the West when built. The bridge is ornamented in a classical style and is listed in the National Register of Historic Places.

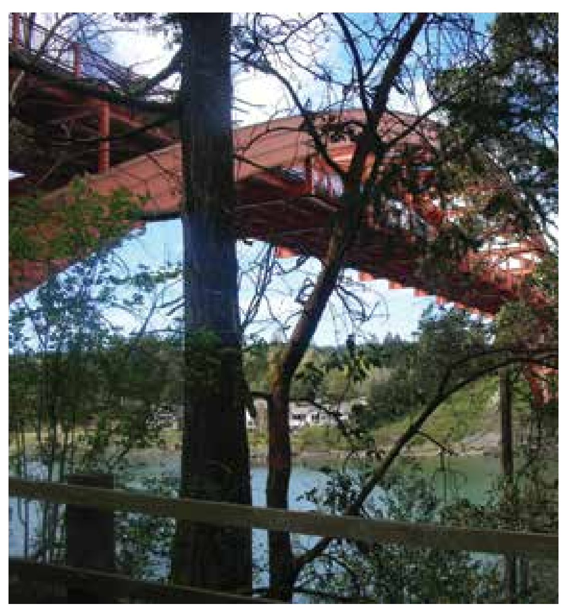
Carbon River Bridge

The Carbon River Bridge, also known as Fairfax Bridge, is a three-hinged, steel-deck arch bridge over the Carbon River, located on SR165 in Pierce County. The arch is comprised of a parabolic-curve steel bottom section, a spandrel braced rib, and a horizontal Warren stiffening truss supports the roadway. The bridge was constructed in 1921 with the following dimensions:

TOTAL LENGTH: 494' | MAIN SPAN: 240' | ROADWAY WIDTH: 17'

The bridge deck rises 250 feet above the rushing river. It was considered the tallest bridge in the State at the time. Tourists from Seattle and Tacoma will use this bridge to travel to one of the most visited Mount Rainier National Park.

The Rainbow Bridge



The Rainbow Bridge is a rainbow-shaped riveted steel through arch over the Swinomish Channel in La Connor, Skagit County. The bridge is painted red. Locally it is called the "Red Bridge". The bridge was constructed in 1957 with the following dimensions:

TOTAL LENGTH: 797' | MAIN SPAN: 580' | ROADWAY WIDTH: 24'

James B. Marsh (1856-1936), an engineer and entrepreneur, developed and patented the "Rainbow Arch", where the crown of the arch is above the deck, the foundation below the deck, and the hangers suspend the deck from the arch. Marsh worked for the King Bridge Company of Cleveland before founded his own Marsh Bridge Company, and successfully promoted the building of the "Rainbow Arch" throughout the United States.

The bridge used the then new high-strength, low-alloy steel in highly stressed areas to reduce weight and cost. It received the AISC First Honorable Mention Award.

The community is celebrating the 60th. Anniversary of the bridge in 2017. The bridge was first lit in early 1990s; but has been dark for the last 7 years. The community has successfully brought the lights back on in celebration of the anniversary!

Hamma Hamma River Bridges

The Hamma Hamma River Bridges are two identical arch bridges spanning the north and south branches of the Hamma Hamma River. Each is a three-hinged reinforced-concrete through arch with a single tied-arch span, located on SR101 in Eldon, Mason County. The bridges were constructed in 1923 and 1924 with the following dimensions:

TOTAL LENGTH: 154' | MAIN SPAN: 150' | ROADWAY WIDTH: 20'

The Hamma Hamma River Bridges are good examples of concrete, ribbed, through-arch bridges commonly built in the U.S. in the 1920s and 1930s. These bridges are listed in the National Register of Historic Places.

Spoken River Bridge at Long Lake Dam

The Spoken River Bridge at Long Lake Dam is an open spandrel reinforced concrete ribbed deck arch over the Spokane River, located on SR231 in the City of Spokane, Spokane County. The bridge was constructed in 1949 with the following dimensions:

TOTAL LENGTH: 486' | MAIN SPAN: 211' | ROADWAY WIDTH: 24'

This is a good example of an open spandrel reinforced concrete ribbed deck arch used in earlier years. "Considere Hinges" were used at the skewbacks to relieve stresses in the arches during construction. A "Considere Hinge" is a temporary hinge that is reinforced and closed with a concrete pour after the dead load has been applied to the arches. It is named for the French engineer Armand Considere, and is listed in the National Register of Historic Places.

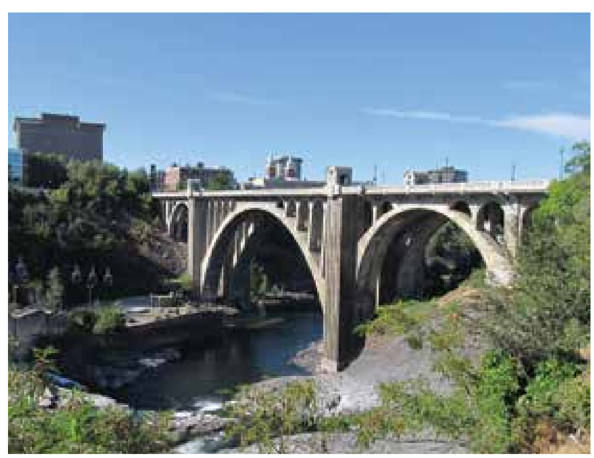
The Blue Bridge

The Bridge Blue is officially named the Pioneer Memorial Bridge, but the locals call this the "Blue Bridge" for the color they picked for the bridge. It is a four-lane steel through tied-arch and truss bridge, located on SR395 connecting Pasco in Franklin County and Kennewick in Benton County. The bridge was constructed in 1954 with the following dimensions:

TOTAL LENGTH: 2,520' | MAIN SPAN: 520' | ROADWAY WIDTH: 66' (4 TRAFFIC LANES + 2 SIDEWALKS)

A U.S. flag flies on top of the bridge, showing the patriotic spirit of the community. It was added during the redecking of the bridge in 1989. It would be quite exciting to walk the bridge to experience the sights and sounds of the tri-cities! The bridge is listed on the National Register of Historic Places.

Monroe Street Bridge



The Monroe Street Bridge is a concrete open-spandrel arch, located in the City of Spokane, Spokane County. The bridge was constructed in 1911 with the following dimensions:

TOTAL LENGTH: 896' | MAIN SPAN: 281' | ROADWAY WIDTH: 50'

When the bridge was completed in 1911, the main span was the longest in the U.S. and third longest in the world. The present bridge is the third one built at this location. The first one was built in 1888. It was a 1,240 feet long, consisting of two wood and steel trusses and wooden trestle approaches. In 1890, a fire destroyed the bridge. In 1891, a steel bridge was constructed to replace the damaged wooden structure. This bridge suffered partial collapse and was declared unsafe in 1905. The present bridge is listed in the National Register of Historic Places

Toutle River Bridges

The twin Toutle River Bridges are riveted steel through tied-arch bridges over the Toutle River at I-5 near Castle Rock, Cowlitz County. The bridges were constructed in 1969 with the following dimensions:

TOTAL LENGTH: 309’ | MAIN SPAN: 304’ | ROADWAY WIDTH: 48’

These two tied-arch bridges are good examples of early years in the design and construction of steel tied-arch bridges. The members tended to be lighter to save materials and costs. Consequently, the lighter structures were more susceptible to large deflection and vibration from the passage of trucks, resulting in fatigue cracking. A program for rehabilitation had to be implemented to minimize deflection, vibration and fatigue cracking.

Cortright Creek Bridge

The Cortright Creek Bridge is a steel arched Pratt deck truss bridge, located on SR12 in Lewis County. The bridge was constructed in 1983 with the following dimensions:

TOTAL LENGTH: 429’ | MAIN SPAN: 275’ | ROADWAY WIDTH: 45’

The bridge is undergoing rehabilitation to control general deterioration. There is no load limit posting of the bridge.

Arch bridges have inherent simplicity and beauty, expression of form and strength, and clarity of function and creativity. They are loved and admired by people of all traits and ages.

Visionary and pioneering leaders in highways and bridge design and construction are duly recognized for their efforts in building the highways and bridges of yesteryears that lead us to enjoy the comfort and speed of highways and bridges of today. This short article with brief descriptions and photos of notable arch bridges of Washington State is dedicated to the men and women who contributed to our comfort and speed in transportation and impact on our daily life. We owe them our continuing dedication and commitment in advancing bridge engineering and technology for safe, durable, efficient, cost-effective and sustainable bridge design and construction.

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4. http://www.wsdot.wa.dot/bridge/structures
5. http://www.bridgehunter.com

Bridge Photo Credits:

Trent Avenue, Selah Creek, Spoken River: WSDOT; Baker River, Hamma Hamma: HAER; Carbon River, Rainbow: J.J. Lee; Blue: Glen Scroggins; Monroe Street: Quinn Phelan; Toutle River: Royce & Bobette Hale; Cortright Creek Mike Goff.

About the author...

M. Myint Lwin is now an independent Consulting Bridge Engineer with special interest and services in bridge engineering education and training, QC/QA, constructability and peer reviews of bridge projects to ensure compliance with the Owner’s requirements, project provisions and Federal and State laws and regulations with emphasis on safety, durability, efficiency, sustainability, and economy. He is the former Director, Office of Bridge Technology, Federal Highway Administration (FHWA), U.S. Department of Transportation, and a former State Bridge and Structures Engineer with the Washington State Department of Transportation before joining FHWA. He is a member of the IBC Executive Committee.

BRIDGE QUIZ ANSWERS: A. The Devil’s Bridge – Sedona, AZ; B. The Rainbows Bridge – Niagara River, downstream of the Falls, Niagara Falls NY/Ontario Canada; C. Natural Bridge – Bryce Canyon, UT; D. Pont Alexandre III over the Seine River, Paris France; E. Bixby Bridge, Big Sur, CA; F. River Liffey (Ha’penny) Bridge, Dublin, Ireland

Arch Bridges

and Pittsburgh's Greatest Bridge Decade

By Thomas Leech & Linda Kaplan

"Works great in one age of the profession will be superseded by greater experience of future times" John B. Jervis, 1869

A Snapshot in Time

The ten-year period from 1924 to 1934 was the greatest bridge decade in the City of Pittsburgh and Allegheny County. There has never been or will their likely ever be, another ten-year period that sees such monumental bridge construction in either the City of Pittsburgh or Allegheny County. Within the greatest bridge decade, eight new bridges were constructed over the three rivers within one mile of the point. In that same time period, many other bridges, both large and small, were constructed over the rivers and valleys of Allegheny County.

The "…greater experience of future times…" was at hand with the completion (in 1932) of the West End Tied Arch Bridge) and the George Westinghouse Bridge, both majestic and iconic arch bridges.

"There are two main divisions of city planning. One look to the rearrangement and improvement of what has already been unwisely done…the other looks to the wise and economical layout of what still remains to be done…" Frederick Law Olmstead, Jr. (world famous landscape architect and son of creator of New York's Central Park) in his Report to the City Planning Commission, 1911.

"…In the early 20th century, planners such as…Olmstead, Jr. … merged park planning and civic art towards a truly comprehensive vision of the organic city…" John Banmen, 2006.

The year is 1932

Two marvelous arch bridges have been completed in the Pittsburgh Region.

The design and construction of these architecturally marvelous bridges was over twenty years in the making. The forces that came to bear were a combination of social, political and environmental. Consider in:

- 1911: Frederick Law Olmstead, Jr.'s seminal urban planning study for Pittsburgh, Report 8, entitled *Pittsburgh, Main Thoroughfares and the Downtown District, Improvements Necessary to Meet the City's Present and Future Needs*, was finalized and presented to the City Planning Commission.

  In his report, Olmstead, Jr., (a leading American landscape architect of the early 20th century and son of the famous landscape architect of New York's Central Park) wryly noted that "Considering the fact that Pittsburgh is a world capital in the steel bridge industry, that its busiest quarters are sundered by three of the worlds big rivers,…it is a striking and rather shameful thing that it does not possess a single bridge over its rivers that is notable among the bridges of the world either for its beauty, for its perfect engineering adaptation to its purpose, for its size, strength or amplitude. In fact, the bridges of Pittsburgh, compared with those of other great cities are rather unusually limited in capacity and lacking in the qualities of impressiveness and beauty."

- 1918: Allegheny County created its own Planning Commission. Over time an intense rivalry developed between the City and County planning commissions as they vied for public money and bonds to finance projects.

- 1924: The Allegheny County Department of Public Works and County Commissions orchestrated a campaign of public support which resulted in the passing of a significant bond measure that funded Allegheny County public works project for the next decade. The County's bond measure funded the construction of all major highway river crossings over all three rivers near the point from 1924 to 1934.

- 1925: Allegheny County, Department of Public Works, with the assistance of Frederick Bigger developed a Major Highway Plan, described as the "Ultimate Highway System" consisting of web-like system of radial and ring roads (presently the color-coded belt designations), centered about downtown Pittsburgh.

With the passage of the 1924 bond measure, and adoption of the 1925 *Major Highway Plan*, Allegheny County looked to implement that part of the plan which would provide boulevard access through the principal river valleys of the region and would move traffic to and from the city, by-passing Pittsburgh at key points.

Ultimately the West End Bridge and George Westinghouse Bridge can be viewed as important but small components of much larger transportation improvement projects. As with the Liberty Bridge and Tunnels, bridges were no longer a just means to convey traffic from one shore to another, but were parts of a much larger and well-orchestrated transportation network. The West End Bridge and its connecting roadway through the Saw Mill Run Valley, as well as the George Westinghouse Bridge, high above the Turtle Creek Valley, and its connection to Ardmore Boulevard, embraced the principles of professional planning sought for in the 1925 *Major Highway Plan.*

The year is 1933

In 1933 the Neal Deal began with emergency legislation enacted to end the depression. This legislation included the National Recovery Administration, Agricultural Adjustment Act, Federal

Emergency Relief, and Works Progress Administration. Pittsburgh anxiously awaited federal money for public works. Little money materialized. With the completion of the West End Bridge and George Westinghouse Bridge in 1932, the era of major bridge construction in Pittsburgh near the point was over and would not return until Pittsburgh's Renaissance and the Interstate Era, in the late 1950's.

Other Notable Bridges Constructed in the City of Pittsburgh and Allegheny County in the Greatest Bridge Decade, 1924–1934, include:

1924: Fortieth Street Bridge (Washington's Crossing) – steel plate girder arch over the Allegheny River.

1927: Second Point Bridge – steel cantilever truss.

1926–1928: the iconic Three Sister Bridges over the Allegheny River – self-anchored suspension bridges, each with 430-foot main spans.

1928: Thirty-First Street Bridge – steel plate girder arch over the Allegheny River.

1930: East Street Bridge – large steel cantilever truss, 225 feet above the floor of the East Street Valley.

1931: McKees Rocks Bridge over the Ohio River – steel trussed arch with a 750-foot main span.

1933: South Tenth Street Bridge over the Monongahela River – steel suspension bridge with a725-foot main span

George Westinghouse Bridge: Perhaps, the Pittsburgh Region's and Allegheny County's most iconic bridge constructed in the greatest bridge decade. Photo Courtesy of the Library of Congress

Pittsburgh Fact: In 1832, a salt processing facility – i.e. salt works - lay along and over Saw Mill Run at its confluence with the Ohio River, at approximately the same location that the west approach to the West End Bridge lies today (from a painting by Russell Smith)." – The small culvert in foreground is Saw Mill Run and the Site of 1832 "salt works.

Pittsburgh Fact: If you are standing on the deck of the George Westinghouse Bridge, 240 feet above the Turtle Creek Valley, and are gazing west, you will see the Monongahela River (9 miles upstream from the point) and Braddock, PA - the site of Braddock's Defeat in 1755 and later the site of the Andrew Carnegie's first steel mill in the Pittsburgh region – the Edgar Thomson Works.

West End Bridge, West Approach - October 1931

Photos Courtesy of Allegheny County, Department of Public Works

The tied arch is a delicate structure. Until the arch was closed the structural form was unstable and an intricate system of temporary support in the Ohio River was required.

About the authors...
Thomas Leech and Linda Kaplan, are bridge engineers, local historians and co-authors of *Bridges…Pittsburgh at the Point …A Journey Through History*. This article has been excerpted from their book which tells the story of the history of the city of Pittsburgh, as seen through the eyes of the 34 bridges that were constructed within one mile of the point. The book charts the rise of the city, the development of transportation and the unique stories of each of the 34 bridges, which for many, no single trace remains. The book may be purchased locally from ESWP and the Heinz History Center, or ordered online from www.woodridgebooksandmusic.com. Also, the authors invite you to visit the book's facebook page at www.facebook.com/bridgespittsburgh to learn more about the book and to view the author's music video, a tribute to Pittsburgh and its bridges.

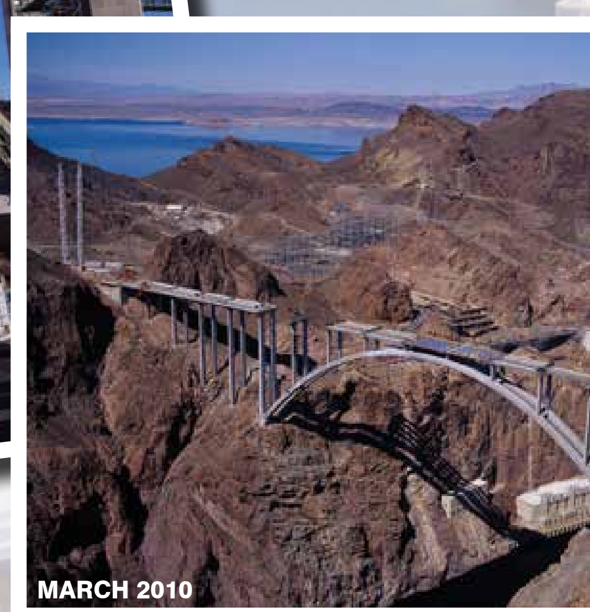
Hoover Dam Bypass Colorad

By Bonnie Klamerus


JULY 2009


AUGUST 2009


DECEMBER 2009


MARCH 2010

Nearly a decade after its opening in October 2010, the Mike O'Callaghan-Pat Tillman Memorial Bridge – commonly known as the Hoover Dam Bypass Colorado River Bridge – stands as an engineering triumph. Spanning the Black Canyon about 1500 feet south of the Hoover Dam and nearly 900 feet above the Colorado River, the 1,900-foot-long bridge offers unparalleled views of one of the nation's greatest engineering icons, and the 3.5-mile-long bypass route benefits transportation and commerce for the thousands of daily drivers on U.S. 93 between Nevada and Arizona, providing significant traffic relief on the roadway atop the dam.

Named in honor of former Nevada Governor Mike O'Callaghan, community leader, war hero as well as businessman and professional football player Pat Tillman, who was killed in 2004 while serving in Afghanistan, the bridge is the highest and longest concrete arch bridge in the northern hemisphere and features the world's tallest precast concrete columns.

Teamwork was a critical factor in the success of the Hoover Dam Bypass project. With U.S. 93 crossing the Arizona/Nevada state line on federally-owned and tribal lands, the project location demanded a multi-agency team comprised of FHWA, the states of Arizona and Nevada, the U.S. Bureau of Reclamation, Western Area Power Administration and the National Park Service. From 1997 through the project's opening in October 2010, the Federal Highway Administration's Central Federal Lands Highway Division (CFLHD) led the complex, fast-paced project completing the environmental process, selecting a world-class consultant team and managing design and construction of all elements of the project. The $240 million project was completed nearly $7 million below its original budget.

Designing for Constructability

T.Y. Lin International led the design of the Mike O'Callaghan-Pat Tillman Memorial Bridge and was instrumental in the integrated engineering analysis during construction. The hybrid structure is one of the first of its kind combining a high-performance concrete arch with a modern steel superstructure - offering advantages for prefabrication and accelerated schedule. Twin concrete arch ribs span 1,060' and precast columns are nearly 300' tall. The concrete bridge deck is supported on four structural steel tub girders per span, and a sidewalk is located on north side affording visitors a spectacular view of Hoover Dam.

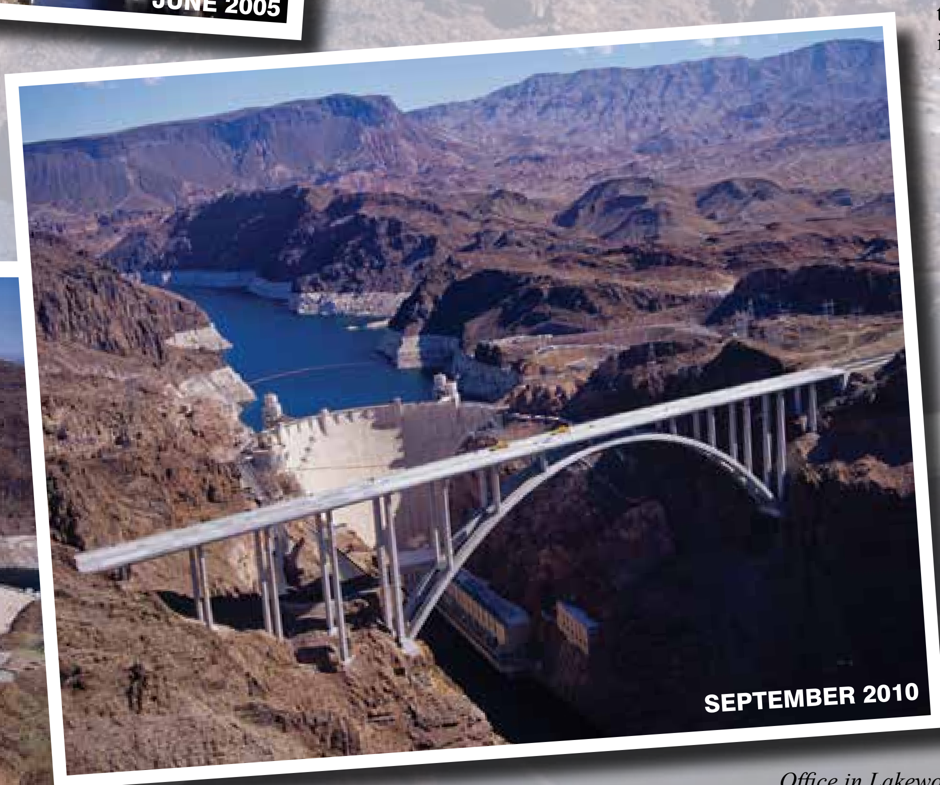
Constructing the bridge using a 50-ton highline cable system was a key assumption that drove many of the design decisions including the superstructure span length and precast column segment size. In addition, a complete erection scheme for cast-in-place cable-stayed arch construction was provided in the plans for the contractor to use at their option.

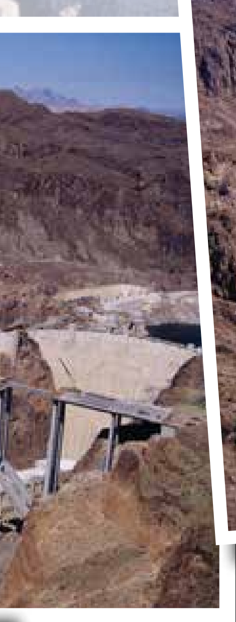
do River Bridge Construction


JANUARY 2008


NOVEMBER 2007


JUNE 2005


SEPTEMBER 2010



Constructing a Long-Span Concrete Arch

The bridge construction contract was awarded in October of 2004 for $114 million to Obayashi Corporation /PSM Construction USA, Inc. (Joint Venture). Construction began in early 2005 in one of the most inhospitable environments and was completed in August 2010, on budget without dispute or claims.

Throughout construction, an overhead highline cableway was used to transport concrete and steel bridge components, as well as workers and materials. A temporary cable supported system using pairs of 150’ tall pylons connected to the deck above the ends of the arch anchored forestay cables attached to alternating arch segments and backstay cables running through concrete anchor blocks off each end of the bridge. High-strength concrete with 56 day compressive strengths of 10,000 psi was needed to handle the design and construction loads on each arch. As arch construction advanced from each side of the canyon, pre-fabricated structural steel struts were installed between the ribs at each spandrel column location. High-strength bars were used to post-tension the strut legs to the arch through ducts cast in the walls of the hollow arch.

The construction met very stringent environmental, design and quality assurance requirements. Because of their size, the arch and columns required integral engineering analysis to maintain tight tolerances. The arches were completed in August 2009 and met within ⅜” of each other. After the temporary cables and towers were removed, precast segments forming the spandrel columns were set in a symmetrical pattern starting at the arch apex. In similar fashion, the tub girders were set symmetrically and post-tensioned across integral concrete pier caps.

Over 1,200 trade and craft workers worked on the six construction projects comprising the Hoover Dam Bypass.

Given the project’s height, construction methods, overall complexity, extreme heat and brutal winds, this modern marvel remains a monumental achievement in large-scale engineering and construction projects.

About the author...

Bonnie Klamerus, PE, is the Supervisory Structural Team Leader for the Federal Highway Administration, Central Federal Lands Highway Division, Bridge Office in Lakewood Colorado. Bonnie was Structures Manager for the Hoover Dam Bypass Design and Construction.

FIXED ARCH

SERVICE LIFE EXTENSION & CORROSION MITIGATION OF THE RAINBOW BRIDGE

The Historic Rainbow Bridge over the Payette River – after mitigation

- Owner: State of Idaho Department of Transportation
- Location: This is historic bridge is in Valley County, Idaho on SH-55 and crossing the Payette River near the town of Smith Ferry.
- Description: The Rainbow Bridge was designed by the State of Idaho and constructed in 1933. It is a steel reinforced concrete arch bridge. The rainbow Bridge is a two-lane, 410 ft. long concrete arch bridge having eight deck spans with eight expansion joints, two abutments, and eight supporting bents. The substructures are cap and column style bents and piers. The arches on both sides of the bridge span over the North Fork of the Payette River and have a length of about 210-feet.
- Project Participants: The key design and construction firms were CH2M-Hill, Corrosion Control Technology, Mowat Construction, and Vector Corrosion Technologies.
- Cost of Project: $455,550.00
- Project Initiation: July 20, 2006
- Completion Date: September 14, 2006

Because of its historic significance (listed on National Register of Historic Places) and strong support from the local community, the Rainbow Bridge was designated for rehabilitation, rather than replacement. After years of exposure to de-icing chemicals corrosion of the reinforcing steel was occurring and beginning to affect the integrity of the structure. The overall scope of the work included concrete patch repairs, replacement of selected items, and rehabilitation of the arches. In the 1990's a previous repair was completed.

During the week of May 3, 2004, a corrosion and condition evaluation of the bridge was completed by Corrosion Control Technologies and CH2M-Hill. This study assessed the extent of corrosion activity and evaluated alternatives for corrosion mitigation, preservation and rehabilitation of the bridge.

The corrosion evaluation consisted of electrical continuity testing, corrosion potential survey, chloride concentrations sampling, and delamination surveys. Corrosion mitigation alternatives considered included impressed current cathodic protection, galvanic anode cathodic protection (aluminum / zinc surface applied metallizing systems and embedded anodes), electro chemical treatments (chloride extraction and realkalization), surface applied penetrating corrosion inhibitors, concrete removal / replacement, drainage control, and waterproof membranes and sealers.

Chloride Extraction – ECE Process – During Construction

As a result of the survey, railings, curbs, and deck expansion joints were to be replaced; the substructure was to be partially patched and reconstructed; and long term corrosion mitigation of the arches was planned. The final corrosion mitigation scheme selected by the DOT was for utilizing embedded galvanic anodes in patches and chloride extraction of the arches.

Corrosion of steel in reinforced concrete can be caused by presence of sufficient concentrations of chloride ions. Chloride ions can destroy the normal passive oxide protection that encases the reinforcing steel, leaving it vulnerable to corrosion. A corrosion mitigation strategy specified and used on this bridge for mitigating corrosion and extending its useful life consisted of two systems:

1. Galvanic anodes where placed in concrete patch repairs to provide localized protection on the deck superstructure. These discrete anodes were installed into and around the perimeter of patches to help prevent ring anode or path-accelerated corrosion and to extend the service life in the chloride-contaminated portions of the existing concrete directly adjacent to the patches.
2. An Electrochemical treatment process or chloride extraction (ECE) was used for rehabilitating and extending the effective service life of chloride contaminated segments of the concrete arch substructure of this bridge. Chloride extraction is a temporary electrochemical treatment process that was used to restore the passive environment around the corroding reinforcing steel in the concrete arches. During operation of this electrochemical process, the voltage and current of the system were monitored and adjusted as necessary to maintain the required current density. Testing was performed before, during, and after treatment to ensure the contract requirements were met or exceeded.

In July, 2006 prior to initiating the chloride extraction process and in September, 2006 after completion of the work, Vector completed half-cell potential surveys in accordance with ASTM C-876-91 and chloride sampling in accordance with AASHTO T260-94.

Unlike a galvanic or impressed current cathodic protection system, the ECE system is a treatment process that removes the cause of the corrosion from the concrete. Also no permanent system is left in place, to be operated, maintained, and monitored for years into the future. Electrochemical Chloride Extraction does not require any equipment or wiring to be left on the structure that can be vandalized or otherwise damaged.

SUMMARY:

ECE was performed only on the main span arches, while galvanic anodes were installed in the patch repairs to provide localized corrosion protection.

Listed below are the many benefits that ECE and embedded galvanic anodes brought to the project.

Electrochemical Chloride Extraction:

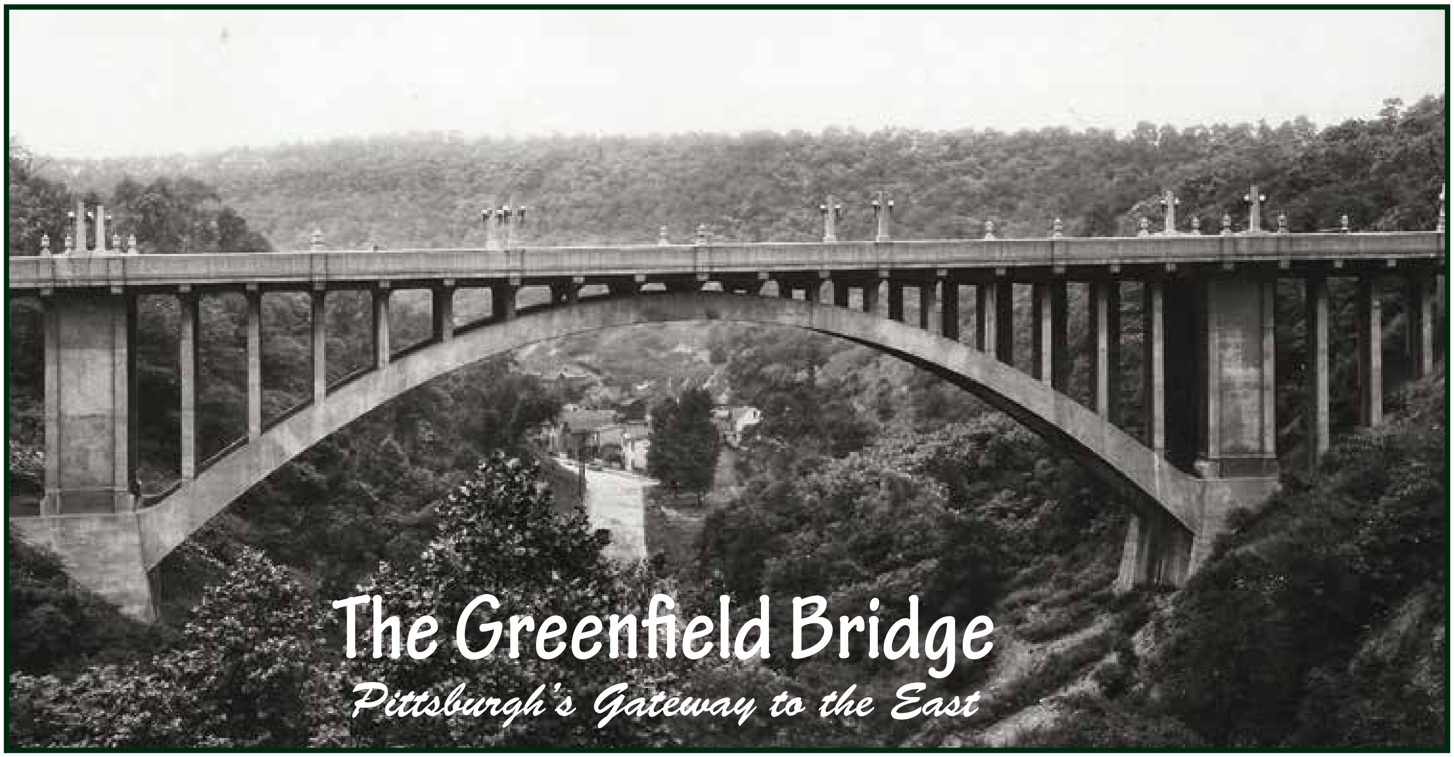
- Removed the source of the problem (corrosion was halted because of the removal of the chloride ions)
- Restored the existing structure vs. replacement
- Minimized traffic interruption because piers were not replaced
- Completed the project during the summer, while with the replacement option, the time frame would have been much longer.

Embedded Galvanic Anodes:

- Addressed localized patch corrosion
- Provided cost saving – fewer repairs will be required in the future.
- Afforded easy installation – no special skills or tools required to install anodes.

At completion of the project the corrosion of the substructure and the concrete arches had been mitigated. Not only were the important structural issues addressed, but aesthetics as well. By including advanced new technology such as Electrochemical Chloride Extraction and Embedded Galvanic Anodes the Owner has taken a bold step in reducing future maintenance concerns while avoiding replacement.

About the author...
Mr. Tore O. Arnsen, P.E., S.E., (retired May 2016), presently acts as Special Projects Engineer for Vector Corrosion Technologies, where he provides technical assistance on an as-needed basis. Prior to retirement, he was Central U.S. Business Development Manager and Representative, where he was responsible to contact, respond to inquiries, and update engineers, Port Authorities, DOTs, utilities and others on the products and technologies available for mitigating corrosion primarily in existing reinforced concrete structures. He was also responsible for over-seeing and managing projects in his area of responsibility. Mr. Arnesen works closely with structural engineers to help repair or rehabilitate structures and extend their useful service life.



Original Arch Structure 1923. Photograph Courtesy of the City of Pittsburgh Bureau of Transportation and Engineering"

By William Beining and Anthony Ream

A landmark arch has linked the Pittsburgh neighborhood of Greenfield to historic Schenley Park since 1922. In that year, a monumental concrete arch was opened to carry Beechwood Boulevard across the valley into the popular park just to the north. Acting as a grand promenade welcoming people to the park, the bridge featured a roadway flanked by sidewalks adorned with decorative urns, pillars, and luminaires.

Thirty years later, with an ever increasing amount of automotive traffic pouring into the city from the east, an Interstate was constructed under the bridge to link downtown Pittsburgh with the eastern suburbs. Interstate 376, known locally as the Parkway East, would grow under the bridge to become the main artery linking downtown Pittsburgh to all points east, and the bridge would become known as the city's gateway to the east.

By the early 2000s, the historic concrete arch that had stood as an eastern gateway for nearly 90 years was showing its age. In the 1980s, a much needed floorsystem replacement stripped some of the bridges grandeur, removing many of the decorative elements. More troubling was the deterioration of the concrete arch rib, resulting in much of the arch being wrapped with protective netting. The "bridge under the bridge" that had been built in the 1990s for a planned rehabilitation was left in place, and became emblematic of the ongoing deterioration of the bridge. In 2012, after years of study and consideration, it became apparent that it was time for a new structure to span the historic valley and act as Pittsburgh's next gateway to the east.

Early in the design of the new bridge, it was decided that an arch was once again the most appropriate form for the new structure. An arch would both meet the structural needs of the site and maintain the gateway nature of the bridge at this historic location. With an overarching goal to minimize impacts to the underlying Parkway, steel was selected as the material of choice for the new arch in part to minimize closure time of the Parkway. The new bridge consists of a 287 foot arch span, with each rib of the arch consisting of just three field pieces of steel. Vierendeel bracing was used for the ribs to minimize members and connections. Additionally, the depth of the floorbeams and stringers were matched to allow for simplified connections splicing the stringer flanges over the floor beam flanges. These design choices would allow the vast majority of the structural steel to be erected in just one weekend closure of the Parkway.

Erection of Structural Steel for New Arch over Weekend in November 2016


Structure After Completion of Steel Erection

Besides the arch shape, other elements of the new structure recall the history of its predecessor. Several original stone architectural elements of the 1922 bridge, including remaining decorative pillars and urns, were salvaged prior to demolition of the 1922 structure. These features were incorporated into the design of the new structure, and will serve to remind users of an earlier time. While these recycled elements help carry forward the past, the new structure goes into the future by connecting the neighborhood of Greenfield to Schenley Park with a widened footprint that welcomes both traditional and non traditional users to journey between the neighborhood and park. Bicycle lanes and a wider than typical sidewalk ensure the bridge acts as an even more effective entryway into the park than before. New decorative light poles and decorative fencing line the travel way, along with the reused architectural features from the previous bridge.

While a design that captured the historic nature of the site was desired, it was also imperative that the new bridge incorporate beneficial design elements in order to provide a new landmark structure that will last well into the 21st century and beyond. One element included the use of the piers to significantly reduce the effects of longitudinal loads such as braking and wind on the steel arch. Due to geometric and aesthetic requirements, the piers have significant strength and stiffness. By fixing the stringer/floorbeam floor system to the piers and using expansion disc bearings at the shortest spandrel columns, the demands on the spandrel columns and associated connections were significantly reduced.

For a steel arch, the floorbeams and spandrel columns are traditionally defined as fracture critical members (FCM) requiring increased material testing and frequent in-depth inspections over the life of the structure. To eliminate the fracture critical designation and eliminate the need for costly in-depth FCM inspections, the floorbeams and spandrel columns were detailed and designed as System Redundant Members (SRM). Redundant members are those whose failure will not cause instability of the overall structure. The redundancy of the floorbeams was achieved and verified through a combination of robust line girder analyses and detailed three dimensional finite element analyses (3D FEA) accounting for the dynamic effects of a floorbeam fracture.

Line girder analyses were used to verify the ability of the stringers and their splices to effectively span two floorbeam bays and also confirm the strength of the remaining floorbeams to support the increased loads. The connections of the stringers to the floorbeams were detailed to resist the high loads. In the event of a floorbeam fracture, the stringer connection effectively becomes a splice at mid-span. The line girder analyses ignore the beneficial resistance of the remaining portions of the fractured floorbeam and three dimensional load sharing of live load across the structure. In addition to the line girder analyses, 3D FEA simulations were used to capture the behavior of the structure during a complete fracture event. The analyses considered different levels of structural damping, time periods for the fracture event and fracture locations (floorbeam mid-span and spandrel support). These parameters were varied to determine the appropriate increase in dead loads to account for dynamic effects. The parametric 3D FEA indicated that the simplified line girder analyses provided more than adequate resistance during a fracture event. Since it was shown that the loss of a floorbeam at its connection to the spandrel would not cause instability in the structure it could then be shown that the fracture of specific spandrel column could be resisted in the same manner.

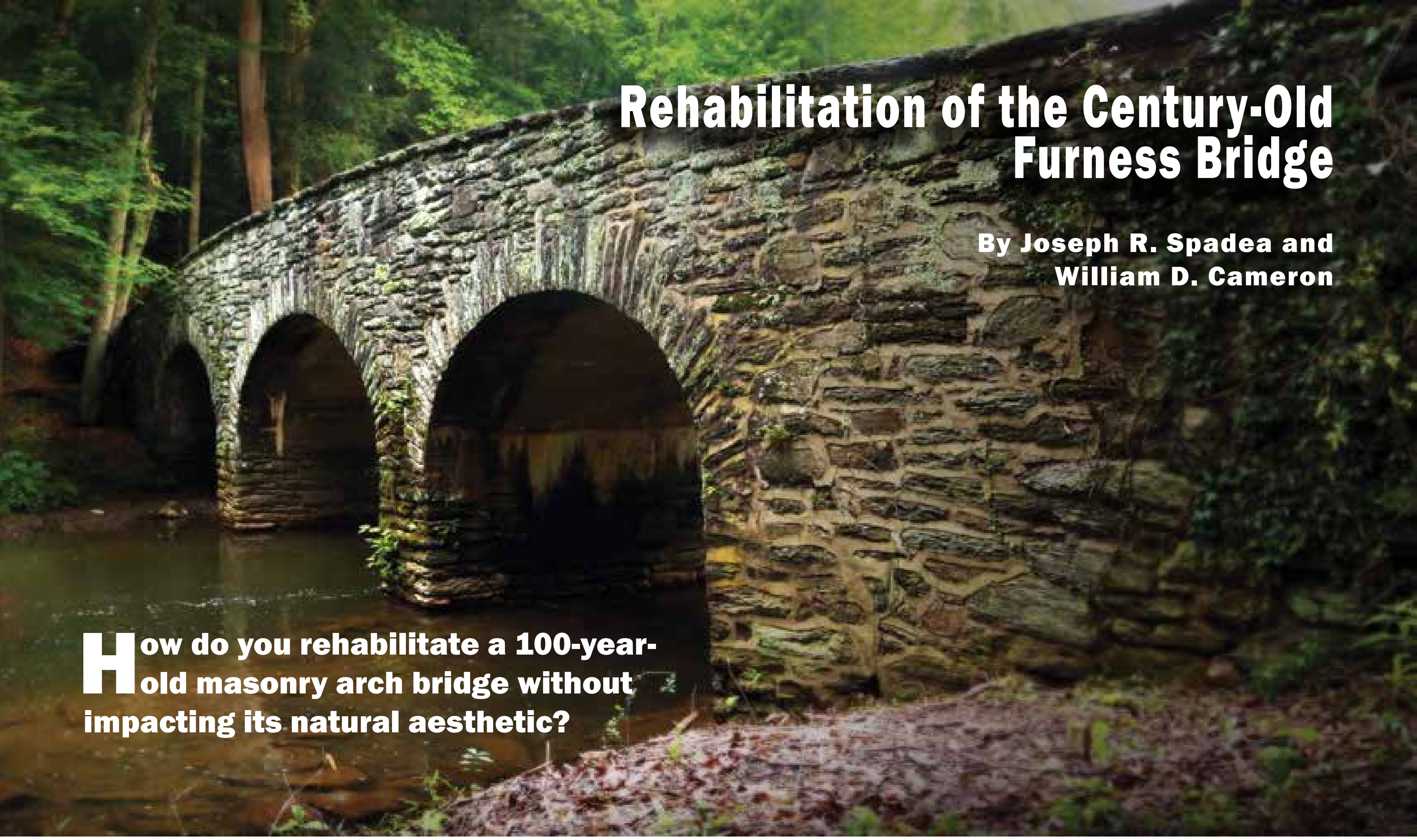
Once completed in the summer of 2017, the new Greenfield Bridge (formally known as the Beechwood Boulevard Bridge) will once again serve as a prominent landmark arch linking Greenfield to Schenley Park and neighboring communities. A pedestrian and bicycle friendly widened footprint flanked with historic architectural elements and decorative lighting will welcome users to with a grandeur reminiscent of the original 1922 structure, while the new steel arch will span the valley and act as Pittsburgh's new gateway to the east. Robust structural design features such as system redundant floorbeams will ensure that this new structure will last well into the 21st century and beyond.

About the authors...

William Beining is a Project Manager and Associate with 19 years of experience at HDR. Anthony Ream is a Senior Bridge Engineer and Professional Associate with 17 years of experience at HDR.

Rehabilitation of the Century-Old Furness Bridge

By Joseph R. Spadea and William D. Cameron



How do you rehabilitate a 100-year-old masonry arch bridge without impacting its natural aesthetic?

Factor in that the bridge is the only access point for a 50-acre family property. These were the challenges of the Thompson Family, owners of the Furness Bridge and descendants of Philadelphia architect, Frank Furness, and influential Shakespearean scholar, Horace Howard Furness.

The Furness Bridge is a 100' crossing spanning Ridley Creek on the charming grounds of the former Upper Bank Nursery in Media, PA. With one of the bridge's three arch spans partially collapsed, the Thompson Family required immediate engineering expertise to ensure their safe passage, and that of any emergency vehicles. Additionally, the family needed a design that would preserve the appearance and legacy of the bridge and its picturesque setting.

Pennsylvania is home to one of the largest inventories of stone arch bridges in the United States. The arch form is both functional and aesthetic and was the natural bridge of choice for early settlers through to the early twentieth century. The Furness Bridge, built in 1916 by Fairman R. Furness, the Thompson Family's great uncle, was no exception. The bridge consists of two 16' spans and one 20' center span. With an overall length of just under 100', the bridge features elliptical concrete arch barrels and stone masonry spandrel walls, piers, and abutments. The use of unreinforced concrete for the arch rings, instead of stone masonry, reflected a shift to using the prominent building material during the period. Fairman Furness, founder of the Upper Bank Nursery, was a charismatic artist, horticulturist, and lecturer. Serving as Third Secretary at a United States Embassy in Russia, he would return home in 1910 to purchase the 50-acre farm which he described as "the Promised Land." Amongst perfectly manicured topiaries, Fairman's bridge also served as a focal point of the nursery entrance.

Within the last two years, members of the Thompson Family sought to develop three of the five lots at the exclusive location. But before this plan could progress, the Family had to be sure that the nearly 100 year old bridge could support the weight of construction vehicles needed to install 600 feet of access roadway to the lots. In addition to the three parcels planned for development, the Family also occupy two existing homes on the land. They too relied on the bridge for access. Given the poor condition of the bridge and inability for fire and medical vehicles to access the occupied homes, the focus shifted to developing an accelerated bridge rehabilitation. Additionally, the design would need to account for pedestrian access during construction. Last but not least, all of the above would need to be accomplished without impacting the aesthetics of the bridge.

Three test pits were excavated along the gravel shoulders to expose the tops of the arches (extrados) to determine the arch thicknesses and confirm the material used to construct the arches. One of the test pits was dug over the center of Span 3 along the left shoulder where lateral movement of the spandrel wall and separation between the arch and the arch ring stones was evident. The tops of the arches at the test pits were found to be constructed of concrete. The edges of the concrete were cast against and, therefore, follow the stone shapes of the masonry ring stones of the arches. This indicated that the spandrel walls were constructed first and used as form work for the concrete arches. Staggered teeth-like horizontal stones were extended from the stone masonry ring stones into the concrete to knit these two components together. The straight lines (not stepped) of the transverse cracks in the arches indicated that the arches are constructed of concrete, not stone masonry. Reinforcement bars or rust stains were not observed at spalled and cracked locations of the arches which indicated the arches were not reinforced.

And with no existing bridge plans available, high-definition (HD) laser scanning was utilized to capture the essential 3D bridge geometry and site topography. The end result of the HD laser scan is a 3D point cloud scale model, yielding accurate and detailed design drawings. Not only did this reduce time recording dimensions in the field, but it also served as a historical record for the bridge.

Fill removed over Spans 1 & 2

Simplified methods were chosen to prepare the analysis and design of the bridge rehabilitation, with consideration of the accelerated project schedule. Using the data obtained from the inspection and the 3D survey scan, a load rating was conducted using the Military Engineering Experimental Establishment Nomograph (MEXE) method of analysis (Department of Highways – UK) as modified by the Department of the Army. The MEXE method uses a practical empirical formula to determine the strength of an arch considering its dimensions, materials, and condition. For comparison purposes, a load rating analysis was also prepared using engineering judgement in accordance with PennDOT's Stone Masonry Arch Methods for Visual Inspection and Load Rating (April 2008) publication. Based on the ratings, it was recommended that the existing structure be posted for a weight limit of 5 tons. If the Span 3 arch's serious condition was not considered (as-built condition), the bridge would still require a weight limit posting of 13 Tons based on the MEXE method. Therefore, to meet the client's goal of no weight limit posting, the bridge within a bridge solution was the preferred alternative.

Removal of failed third span arch

Based on the findings and needs of the family, Pennoni proposed to rehabilitate the bridge from inside out by constructing a new bridge within the existing structure. The design would call for the removal of the roadway and earthen fill over the existing concrete arch rings and masonry walls. The non-structural fill would then be replaced with a reinforced concrete slab made integral with two of the existing arch spans and masonry façade. The compromised third span arch ring required complete replacement. The design also included a stream ford style crossing to maintain pedestrian access during construction. The crossing utilized standard PennDOT-approved details and doubled as access for construction vehicles and workforce.

The design also called for a waterproof membrane to be placed on the proposed slab to minimize water intrusion over the bridge and abutments. To facilitate utility installation for the new development, provisions were included for future gas, electric, and communications lines to be encased beneath the new bridge deck.

Geotechnical test borings were ordered and taken through the center of the masonry piers to determine if the existing stone masonry piers could support design vehicles. The borings were used to calculate the strength of the piers, which were found to be adequate. They also revealed that competent bedrock underlain most of the bridge. Undermining of the piers and abutments was observed during an initial inspection; therefore, waterline concrete aprons were designed for the piers and abutments as an effective long-term scour countermeasure. The apron design called for keying into the relatively shallow bedrock, with removed material to be repurposed as additional scour and channel protection.

Using a simplified practical approach was continued during the final design. The proposed structure was designed using the PennDOT LRFD Box Culvert Design and Rating (BXLRFD) computer program. The structure type included a two span frame with no bottom slab. The maximum haunch depth allowed in BXLRFD of 30 inches was used to simulate the arch shape. The results generated were used to size the footings, walls, and continuous slabs and the reinforcement bars. The two span results were extrapolated for the third span.

The existing stone masonry wingwalls were to remain at the west abutment. New reinforced concrete walls to be cast against the existing wingwalls were designed using the PennDOT LRFD Abutment and Retaining Wall Analysis and Design (ABLRFD) computer program. At the east abutment where the wingwalls exhibited movement, new wingwalls with stone facing were designed. Existing stones were reused for the stone facing.

Test borings were drilled through the existing piers to determine their profile. Pier 2 was found to not extend to bedrock and scour was present. Drilling pin piles through the existing stone masonry and concrete piers was examined. However, surrounding the piers with reinforced concrete aprons keyed into bedrock was selected due to lower cost, ease of construction, and to address stream scour issues.

The concrete of the new bridge within the bridge was placed in lifts and allowed to cure to minimize unbalanced loads and to strengthen the arches prior to adding the next layer of dead load.

The steps of construction included:

1. Installing a causeway and cofferdams
2. Installing concrete aprons at the abutments and piers
3. Installing horizontal bracing in Span 2 prior to removing Span 3 to address the unbalanced arch loading caused by the removal of Span 3. The original design had beams placed in Span 3 for this purpose: however, the contractor decided to instead install steel rods in Span 2.
4. Installing a temporary pedestrian bridge at the causeway

Furness Bridge After Rehabilitation

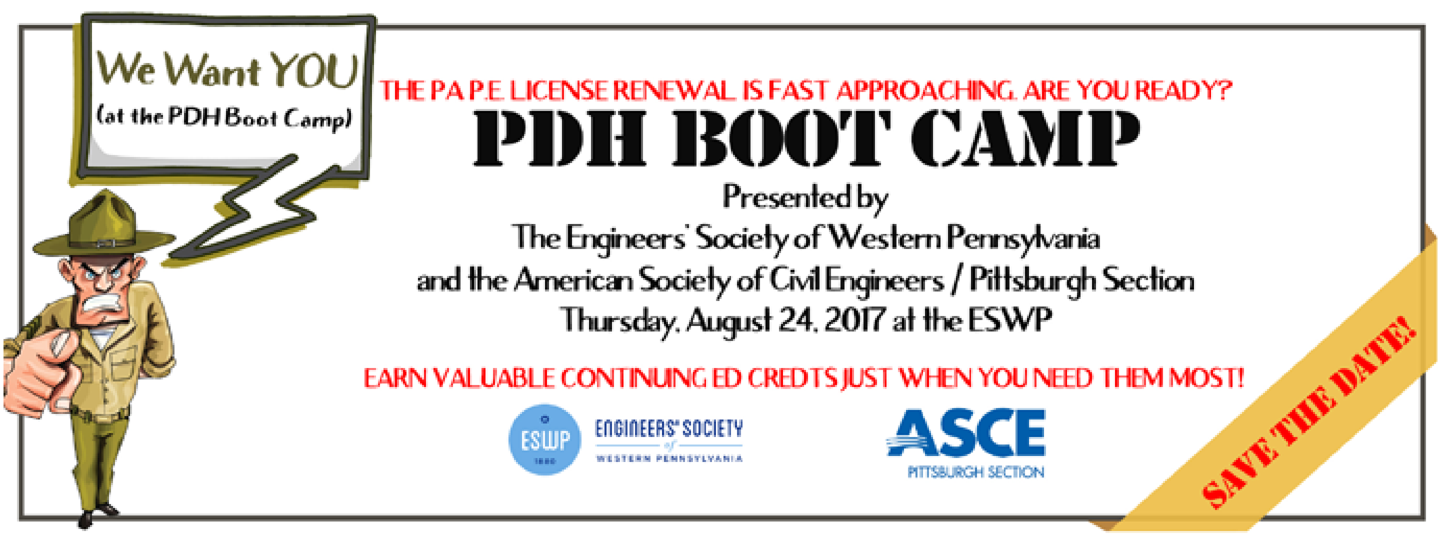
5. Removing the fill above the arches
6. Constructing the west abutment (Abutment 1) and west wingwalls behind the existing abutment and wingwalls
7. Placing the first two lifts of concrete in Spans 1 and 2 to strengthen the spans
8. Removing the failed Span 3 and salvaging the existing spandrel wall stones for future use
9. Constructing Abutment 2 and the east wingwalls
10. Constructing the Span 3 arch
11. Backfilling the abutments
12. Placing the final lift of concrete, which is the continuous concrete slab
13. Placing a membrane waterproofing and bituminous wearing surface
14. Opening the bridge to limited traffic
15. Finishing the remaining stone masonry placement and repointing to complete the project

Although price was considered, final contractor selection was based on qualifications, responsiveness during the invitation to bid period, and approach to completing the project. Specialty bridge contractor J.D. Eckman, Inc. of Atglen, Pennsylvania as selected to perform the rehabilitation work. Construction commenced in July 2015 and was completed in December 2015 – approximately one year after initial concerns arose. Upon completion, the aesthetics of the Furness Bridge were preserved. The bridge can support the weight of modern construction and emergency vehicles and is capable of providing another century of service.

A brief documentary of the project is available at www.Pennoni.com/FurnessBridge

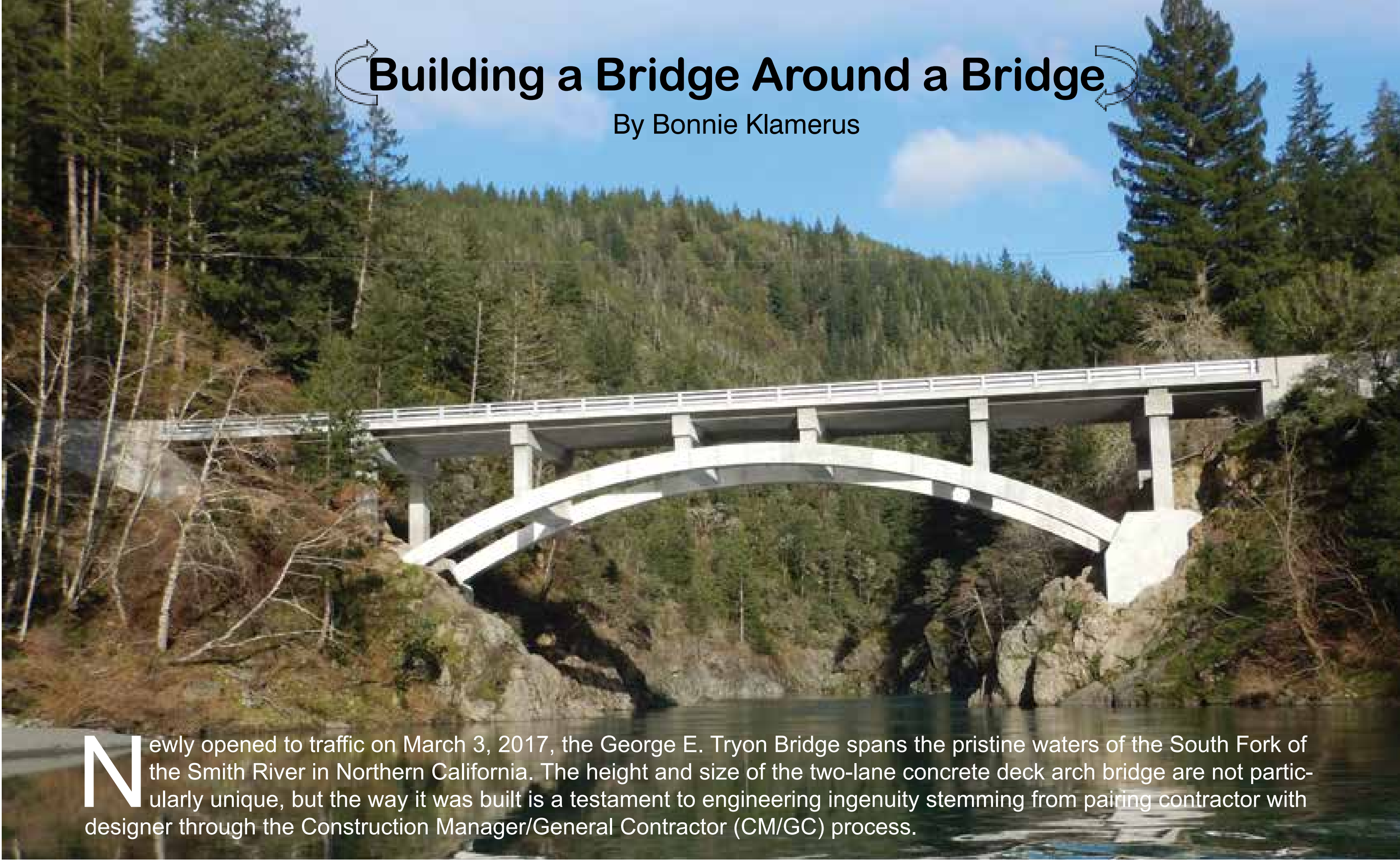
About the author...

Joseph R. Spadea, P.E., is a Senior Engineer and Project Manager at Pennoni, part of the Bridge and Transportation Division in Newark, Delaware. William D. Cameron, P.E., is also a Senior Engineer and Project Manager at Pennoni, a member of the firm's Mechanicsburg, Pennsylvania Bridge and Transportation Division.



Building a Bridge Around a Bridge

By Bonnie Klamerus



Newly opened to traffic on March 3, 2017, the George E. Tryon Bridge spans the pristine waters of the South Fork of the Smith River in Northern California. The height and size of the two-lane concrete deck arch bridge are not particularly unique, but the way it was built is a testament to engineering ingenuity stemming from pairing contractor with designer through the Construction Manager/General Contractor (CM/GC) process.

Looking upstream at the new George E. Tryon bridge with twin fixed arch ribs spanning 141′-3″ with a 19′-0″ rise. Rib members are 3′-6″ wide by 4′-0″ tall and are spread 29′ apart.

Project Need and Sensitive Site

The original historic George E. Tryon steel deck arch bridge was rated as structurally deficient and fracture critical with seismic vulnerability and deteriorating structural steel and paint. Due to the historic nature of the existing bridge and views of the bridge from California U.S. Highway 199, a two-lane concrete deck arch with twin ribs was selected as the replacement structure.

The Central Federal Lands Highway Division (CFLHD) of the Federal Highway Administration (FHWA) partnered with the Six Rivers National Forest and Del Norte County to lead the design and construction of the project. Located on County Road 427, locally known as South Fork Road, the route serves as the primary access to three residential communities and provides access to the Six Rivers National Forest and Jedediah Smith Redwood State Park. Maintaining public traffic was a key requirement, however curvilinear approach roadway alignment and limited staging areas complicated construction at the constricted site.

The South Fork of the Smith River is designated as a Wild and Scenic River and the project site is an extremely sensitive cultural and natural setting with threatened and endangered species of birds and fish. The gorge has steep, rocky sides with a popular beach and swimming hole directly downstream of the existing bridge.

Builders of the original bridge in 1948 took advantage of the natural rock outcroppings at the narrowest spot in the river for foundation support. Thus, the ideal location for the new George E. Tryon concrete deck arch bridge was on the existing alignment in order to build the shortest bridge while maintaining a rise-to-span ratio similar to the old bridge without dramatically raising the roadway grade. This location also lessened the permanent environmental and right-of-way impacts and provided natural tie-ins to the existing roadway. However, the requirement to maintain traffic during construction left few options other than building a costly 300-foot long detour bridge next to the old bridge with temporary bents in the river that would cause serious environmental impacts.

CM/GC Delivery Shapes the Project

Because of the challenge of constructing an arch bridge at a constricted site under complicated project conditions, CFLHD realized that contractor input was vital to the success of the project. As a result, the Construction Manager/General Contractor (CM/GC) delivery method was chosen early in the project development process to help mitigate risk, incorporate constructability considerations, realize cost savings, and limit environmental impacts. Using a competitive “best value” process, Flatiron West Inc. (FWI) of Benicia, California was selected as the CM/GC contractor in September 2013. Since CM/GC has had limited use on public projects in California, Flatirons West, Inc. was anxious to add the County project to its resume.

Shortly after contract award, FWI proposed an innovative staged construction scheme to build the new bridge around the old bridge and eliminate the need for a detour bridge.

Looking upstream during one of the arch rib concrete pours as truss bridges support the formwork, reinforcing steel and concrete ribs. Work platforms are hung from the old bridge.

In coordination with FWI, a revised layout was developed by CFLHD with the old bridge left in place during much of the new construction. New abutments were set back behind existing abutments. Arch footings were positioned outside the four existing footings which were permanently left in place. The arch profile was lowered so that the soffit sat below the existing steel arch ribs. Columns and struts were strategically located to avoid conflicts with the old bridge components. The roadway and deck elevation was raised approximately six feet to facilitate stage construction of the superstructure and precast I girders were replaced by precast slab beams for a shallower profile.

The original bridge viewed from downstream.

Construction Challenges

Bridge construction began in June 2015. One of the initial challenges facing Flatiron crews was accessing and excavating the arch footings on the steep, rocky cliffs of a 50-foot deep gorge. Blasting rock for the new arch footings was not an option because they were adjacent to and below the bottom of the existing footings which continued to support the old bridge under traffic. Jack hammering, a tedioius endeavor, was used to break the rock which was then manually lifted out in small buckets. Once excavation was complete, micropiles were installed on the angled back face and concrete was poured.

Arch construction was the next challenge. Due to environmental restrictions, falsework supports were prohibited below the ordinary high water limits requiring to overhead support of arch construction. Unfortunately, the existing steel arch was not capable of handling much more than its own weight plus traffic so supporting the arch formwork and concrete from the old bridge was out of the question.

After much study, the contractor decided to use an innovative method for arch construction using an ACROW truss bridge positioned above each rib set alongside the old bridge and supported on temporary steel falsework bents founded on the new arch footings. Tie rods connected the wooden arch formwork to the truss and the system was laterally braced by the old steel ribs. Once the concrete achieved strength, the truss bridges were removed and the spandrel columns were built on the ribs.

The photo shows the upstream view of the completed arch ribs, columns, cap and struts before the Stage 2 superstructure was constructed. The existing bridge has been demolished and removed.

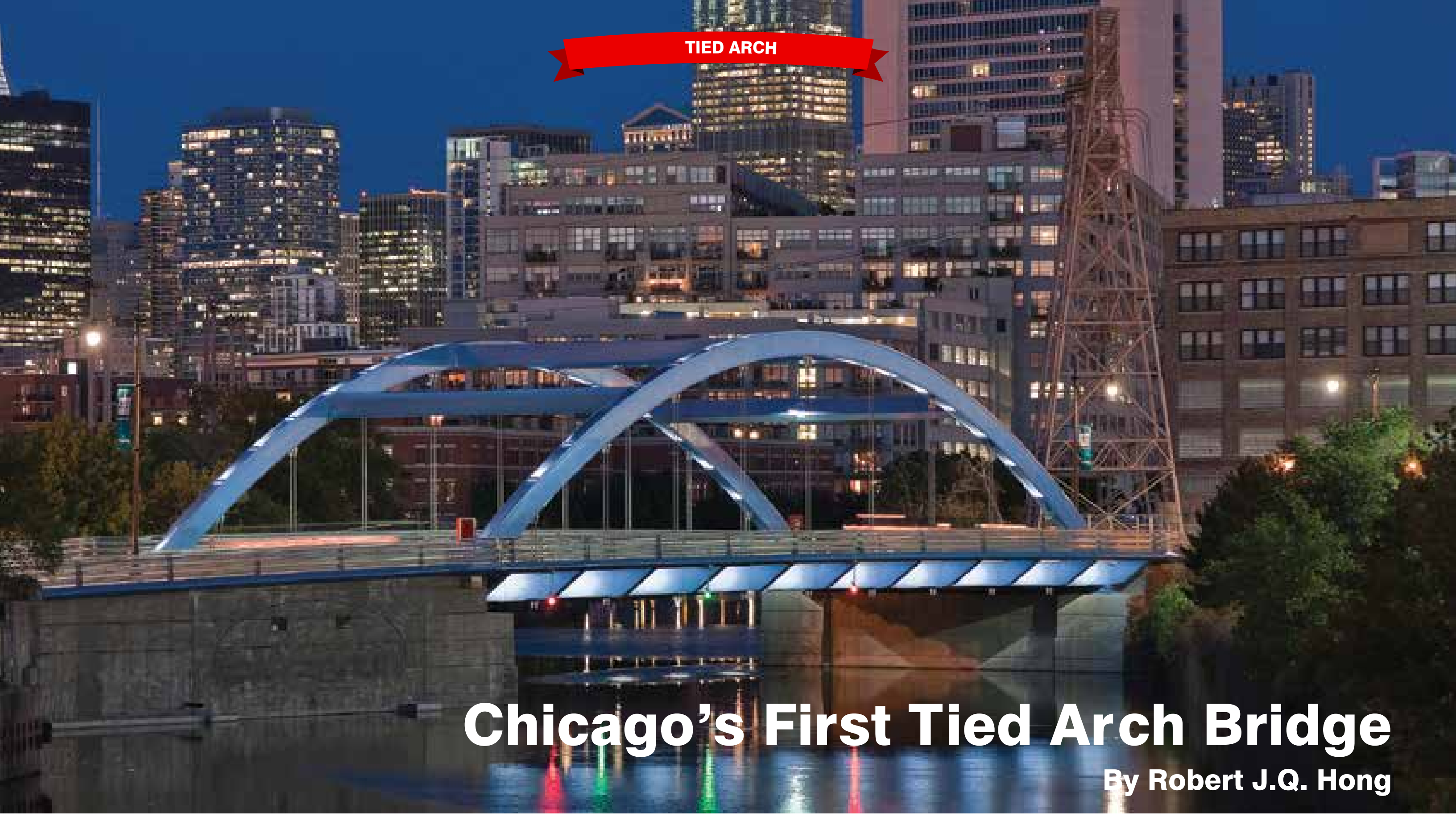
Half of the old bridge superstructure was then removed. Construction of partial-width pier caps and superstructure supported by heavy falsework continued while traffic remained on the other half of the old bridge. Once traffic was shifted to the new deck, the remainder of the existing bridge was delicately removed from above and the other half of the pier caps and superstructure were completed.

Conclusion

Motorists travelling on California U.S. Highway 199 may not even notice the new George E. Tryon Bridge sitting peacefully above the often tranquil, aquamarine waters of the South Fork of the Smith River. But thanks to the ingenuity and collaboration between engineers and builders through the CM/GC process, an arch structure that mimics the original was constructed from above without touching the water and with ultimate respect for the environment.

About the author...

Bonnie Klamerus, PE, is the Supervisory Structural Team Leader for the Federal Highway Administration, Central Federal Lands Highway Division, Bridge Office in Lakewood Colorado.



Chicago's First Tied Arch Bridge

By Robert J.Q. Hong

A few years ago, the Halsted Street Bridge over the Chicago River North Branch Canal put in its 100th year of service.

Built in 1908, the movable double-leaf trunnion bascule truss bridge provided navigable waterway accessibility for vessels too high to pass beneath when it was closed. Due to the cost of maintaining a movable bridge and the lack of high-mast vessels using the canal, however, the moveable mechanisms of the bridge were decommissioned over 25 years ago and the movable spans were locked together in the closed position.

More recently, the bridge became identified as the only remaining bottleneck to Halsted Street traffic, the central artery of Chicago. In addition, the bridge had become structurally and functionally obsolete (in 2007, it earned a sufficiency rating of 25.9 out of 100), and the Chicago Department of Transportation (CDOT) retained structural engineer Lochner to design a replacement.

Four different bridge alternatives were considered and evaluated for cost, timeline for construction, aesthetic value, constructability and impact on the environment and community: a haunched steel plate girder bridge, a multi-span precast concrete arch bridge, a steel through truss fixed span structure and a steel tied arch bridge. CDOT selected the steel tied arch option, and bridge design took place between 2007 and 2009. Construction began in November 2010 and the new bridge was opened to traffic in December 2011.

The new replacement structure consists of a 157' long and 80' wide steel tied arch bridge main span flanked by two 36' three-sided precast concrete arch approach spans. With the new bridge deck 22' wider than the existing bridge, the replacement bridge carries two lanes each of northbound and southbound vehicular traffic, with one bike lane and pedestrian sidewalk placed on each side. The precast concrete arch approach spans provide the east- and westbound pedestrian access for a future extension of the Chicago Riverwalk under the bridge. A 12' 4" vertical waterway clearance is provided allowing small boat traffic to pass under the bridge main span. As a cost-saving (and environmental) measure, a portion of the existing bridge substructure was reused to support the precast concrete arch approach spans.

ELEGANT ARCHES

The distinguishing characteristics of tied arch bridges have long been regarded as an elegant solution for long-span crossings. However, very few short-span tied arch bridges have been built recently in the U.S. due to concerns regarding redundancy and constructability of the structural system. Three techniques in particular assisted in bringing the Halsted Street Bridge together:

BOLTED WEATHERING STEEL TIE GIRDERS.

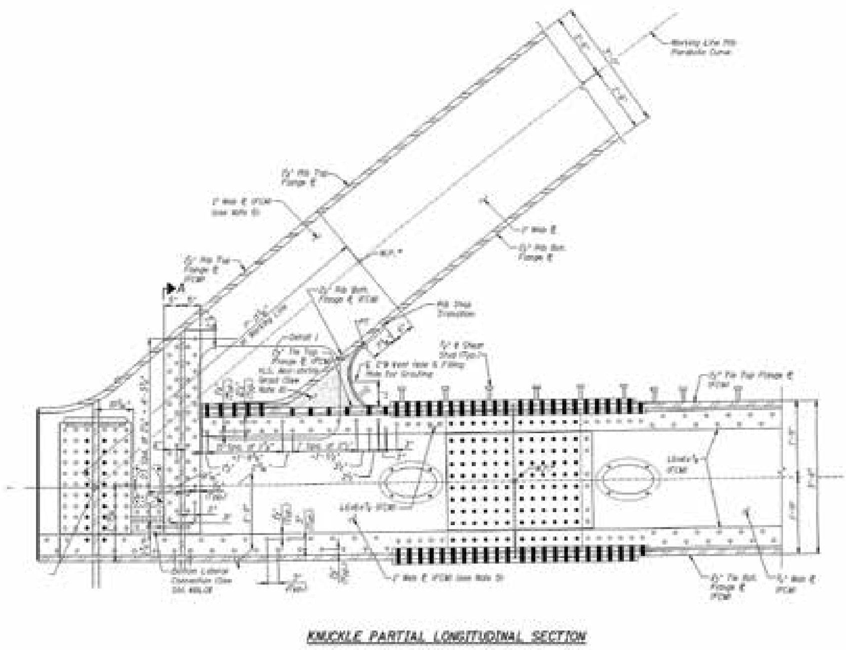
Because the two tie girders carry the tension forces to support the weight of the entire bridge, any loss of these members would result in catastrophic structural failure. Hence the ties are classified as fracture critical members (FCM). This characteristic prompted a Federal Highway Administration (FHWA) advisory in 1978, recommending the improvement of the redundancy. Since that advisory, few tied arch bridges have been designed until recently. The 2' 6" wide by 3' 6" deep steel tie box girders of Halsted Street Bridge are built up from four plates joined using bolted angle connections in each corner. This design arrangement provides a higher degree of internal redundancy and helps address the issues raised in the FHWA Advisory. Welded members tend to propagate fractures into the adjacent plates; whereas the discontinuity created at the bolted connections will arrest the crack and prevent losing the entire section.

CONTINUOUS AND COMPOSITE FLOOR/TIE SYSTEM.

The continuous and composite floor/tie system not only allows the use of a much shallower superstructure to maximize the navigational clearance, but also provides an additional load path to resist global tension force in the event of failure of a tie member. This design mechanism results in a much more economical, durable and redundant floor system.

LOAD PATH REDUNDANCY BUILT INTO THE CABLE HANGERS.

Part of the load path redundancy is achieved by providing a pair of ASTM A586, Class A/C structural strands at each hanger location. Each of the two structural strands are fully capable of supporting the full bridge service loading under the temporary condition when the other structural strand is damaged or decommissioned from service due to maintenance or repair. This design arrangement makes it possible for the maintenance crew to service the cable hangers without closing the bridge to traffic.



Knuckle Details

PLEASINGLY PARABOLIC

The bridge's arch rib follows a line of parabolic curve with a vertical rise of 35' and a span of 157', resulting in a rise-to-span ratio of 1:4.5. The bridge consists of nine equally spaced hangers at 15' 6". The floorbeams are supported from the structural strand hangers anchored at the bottom of the tie girder and attached to the bottom of ribs using steel gusset plates and open sockets. The gusset plates penetrate the rib and are bolted to the stiffener plates that are welded to the inside face of the steel ribs to transfer the hanger forces into the rib. The arrangement of this connection detail ensures a continuous smooth rib surface without bolt connections being exposed.

The arch ribs are spaced at 60' center-to-center; the rib element is a 2' 6"-wide by 3'deep welded steel box. For simplicity, the rib is braced with a lateral system that consists of only four top struts rigidly framed with the ribs. The small size of the closed box section of the tie girder inhibited ironworkers from accessing the interior during erection. As such, hand holes were provided on the web plates of the tie girder at each connection between the floorbeam and tie and at each tie girder field splice location, which allowed the erector to make field connections from outside the box. In addition, the interior of the tie girder is painted bright white for the convenience of future inspection via cameras through the hand holes.

One of the challenges during the design was to control and minimize the large torsional moments imposed on the tie girder. Through camber of the floorbeams and rib top strut bracings, temporary global counteracting torsional moments were introduced into the tie girders when the arch members were forced to close during the connection of the top struts. This procedure helped reduce the permanent torsion in the tie girder and thus minimize the size of the steel ties and its splice connections.

Other members that were cambered include arch ribs, ties and cable hangers. For tied arch bridges, which are designed as rigid moment frames in nature, member cambering not only achieves a desired final bridge geometry, but also helps to reduce the member forces by injecting a counteracting force into the structural system through erection. Similar to the "prestressing" concept used for the concrete structure, introduction of the counteracting forces imposing on the steel structural system during erection allow the design to minimize the structural size and maximize the efficiency of the steel usage. Although the savings of the structural steel to the project was a direct benefit, additional indirect benefits included the use of lighter falsework and reduction in demand for the crane capacity.

A conventional floating stringer and deck system was used for the bridge, with stringers framed into the floorbeams via bolted shear connections. However, at one end of the connection, short slotted holes were used and the bolts installed in the slotted holes were only finger tightened during steel erection. This allowed the structure to elongate during steel erection and concrete deck placement, which prevented accumulation of tension forces in the stringer with all dead-load tension force carried by the tie girders alone. After the concrete deck was placed, the connection of the bolts in slotted holes were then fully impacted and tightened.

Pot bearings were placed under the knuckles at four corners under the bridge floor system. The bearing stiffeners and jacking stiffeners all needed to be placed in the knuckle, which posed a formidable challenge for the designers to not only meet the requirements of connecting different geometrically configured components but also to satisfy the strength demand for each of these components within a very confined space. Because the knuckles had to be capable of carrying the entire global tensile force in their respective webs, finite element analysis was performed to ensure their structural adequacy.

The contractor, Walsh Construction, had the option of construct-

Floor System During Erection

ing the main arch span off-site, floating it in and lifting it into place or constructing the span on-site, over the river. Considering the limitations of the crane capacity and the difficulty of the barge transportation due to the silted river bed, the span was built on-site. On Christmas Eve of 2011, the main construction of the project was complete and Halsted Street Bridge was open to vehicular and pedestrian traffic on schedule. The total project construction cost was $13.7 million, well under the allocated city budget for this project.

FUTURE VALUE

The short span tied arch bridge is a valid design option for enhancing an urban setting with an aesthetically-pleasing structure and spurring local economic development. The successfully completed Halsted Street Bridge demonstrates that a short-span tied arch can be done economically with attention to the steel details that accommodate both aesthetics and constructability. Plus, its size speaks to its adaptability and usefulness in tight quarters and it validates that site issues can be overcome by thoughtful design.

Owner: Chicago Department of Transportation

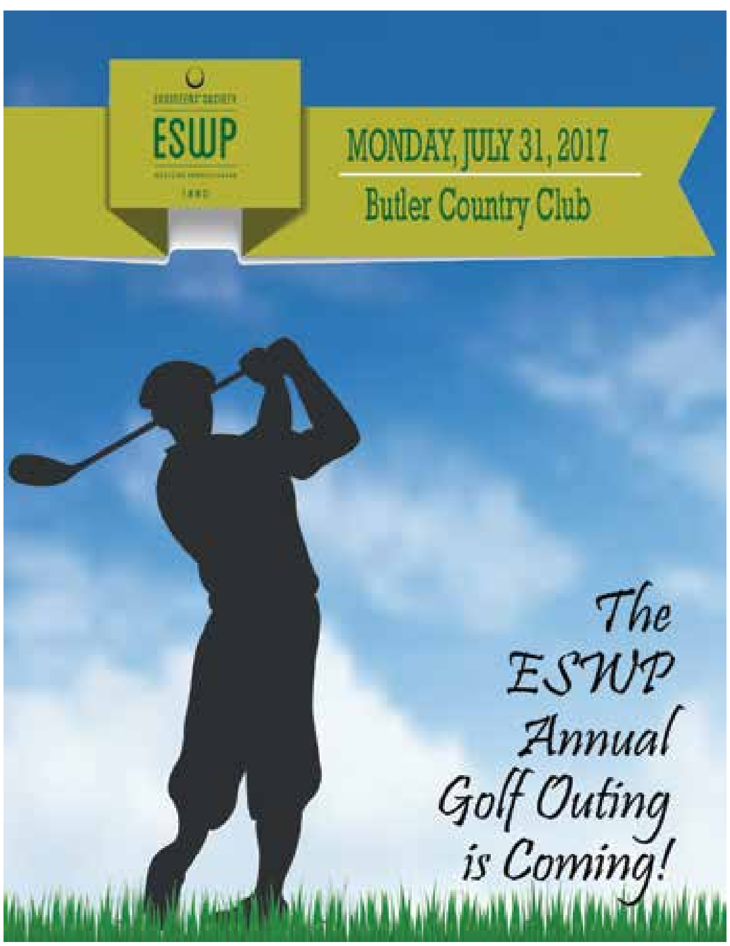
Structural Engineers: H.W. Lochner, Chicago (Prime Consultant)

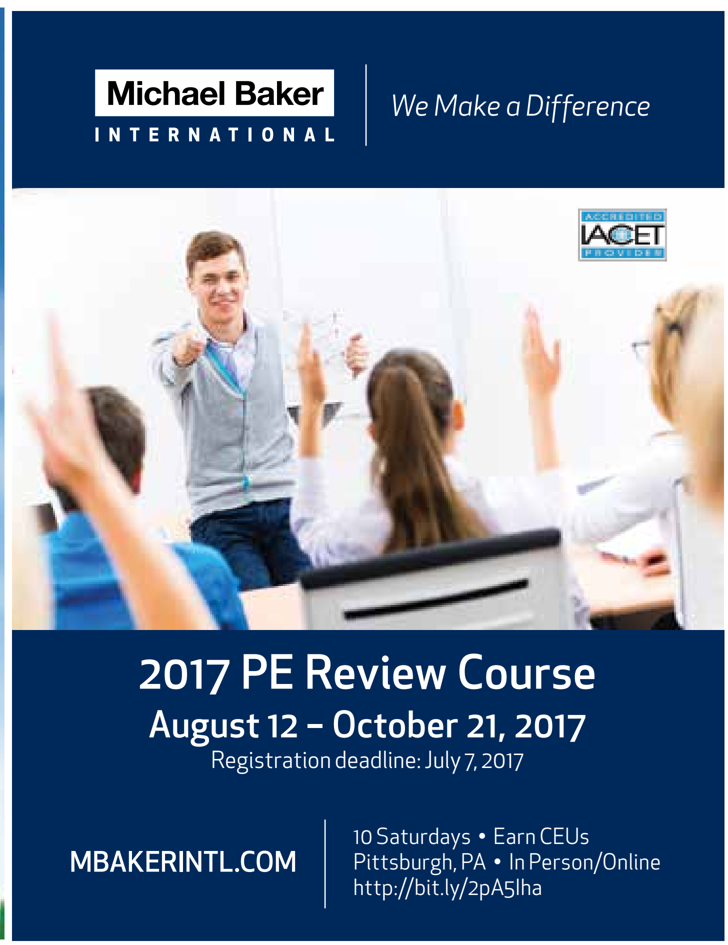
HBM Engineering, Chicago (Subconsultant)

General Contractor: Walsh Construction, Chicago

About the author...

Mr. Robert Hong, P.E., S.E. is a Lead Structural Engineer and Project Manager in Lochner's Midwest design group with more than 22 years' structural design experience within the transportation industry.





DESIGN & CONSTRUCTION Of The MICHIGAN GATEWAY TWIN ARCH BRIDGES

By Ihab Darwish
and Muthiah Kasi


Elevation View of the Michigan Gateway Twin Arches

PROJECT OVERVIEW

Telegraph Road twin arch bridges were part of a number of improvements along the 18 mile I-94 corridor between Detroit airport and downtown Detroit. The bridges are located in Taylor City, 4 miles northeast of the Detroit airport and approximately 13 miles west of downtown Detroit. The bridges carry westbound and southbound of I-94 traffic over a new reconstructed interchange at Telegraph Road (US-24). The interchange is a Single Point Urban Interchange (SPUI) which limits the needed Right-of-Way (ROW) to minimum. The SPUI requires the bridge to be a single span. Designing a conventional single-span girder bridge would require raising the I-94 profile significantly in order to achieve the required vertical clearance over Telegraph Road. An arch bridge was proposed to avoid this raise, maintain clear sight distance and improve aesthetics. The bridge design went through several iterations in order to meld engineering functions and aesthetic quality.

BRIDGE DESCRIPTION

Each structure is a single span inclined through arch. The interior and exterior arch ribs are inclined 25 degrees towards each other. The ribs are braced together using five football shape braces. The bases of the exterior arch ribs are located at Telegraph Road, while the bases of the interior arch ribs are located at I-94 level. This caused the length of the exterior rib and the interior rib to be different. The length of the exterior and interior arch ribs is 296' and 257', respectively. The span length measured between the east and west abutments is 246'. The arch ribs are 3'x 4' box-sections. The webs of the ribs are ¾" thick. The flanges for the exterior ribs and interior ribs are 2 ½" thick and 2 ¼" thick, respectively. The superstructure is comprised of a 9" thick, cast-in-place reinforced concrete deck, four W 18x65 stringers and two 38 ½" deep stiffening girders, all supported by fourteen transverse steel beams that are equally spaced at 16'-5". The transverse beams, stiffening girders, and stringers are composite with the deck.

The transverse beams are haunched I-beams with portions of the beam extending outside of the deck. These portions are boxed using two additional outer webs. The boxed-sections of the beams improve aesthetics and increase the torsional resistance of the beams in case one strand within the hanger assembly is lost or replaced.

The superstructure is supported from the arch ribs by hangers. Each hanger assembly consists of two-2 ⅛" diameter, ASTM 586 structural strands that are spaced 1'-3" center to center. The inner wire of each strand is galvanized with a Class A coating while the outer wires are galvanized with a class C coating. Each strand is anchored to the end of the transverse beams using a Type 6 socket and attached to the ribs using 1 ¾" thick hanger support plates and open type sockets.

PRESSURIZATION

Due to the small size of the arch ribs, future inspection and maintenance of the inside portion of the box is difficult. Therefore, arch ribs, braces, and the boxed sections of transverse beams are pressurized with air to prevent moisture and eliminate potential corrosion. The pressurization of the sealed chambers was performed before the steel members were shipped to the site. First, the atmospheric pressure inside of the sealed box section was reduced by 10 psi. Air at a maximum relative humidity of 20% at 50° F was then pumped into the sealed box member to a maximum pressure of 8.0 psi gauge pressure. The air pressure in each box section, ambient temperature, and adjusted pressure were recorded with the particular member location on the bridge. Additional pressure readings were taken at the air pressure value after 24 hours, after one week and at the time that the box member is shipped from the fabrication facility.


Exterior Longitudinal Foundation Tie with Waterproofing Coating

BRIDGE FOUNDATION SYSTEM

Semi-integral abutments and arch rib thrust blocks are founded on reinforced concrete pile caps. The caps are supported by HP-piles. The interior arch ribs for the two arch bridges are supported on a common thrust block that is located between the abutments of the two bridges. Considerable settlements were expected behind the abutments of the bridges. Therefore, light-weight expanded polystyrene (EPS) foam blocks were placed behind the abutments and interior thrust blocks.

In true arches, the longitudinal arch thrust is taken by the foundation supports, such as the piles. In a tied arch, the thrust is taken internally by the tie. For this modified tied arch, the longitudinal arch thrust is resisted by multiple foundation elements; the longitudinal reinforced concrete foundation ties, the transverse foundation ties and the battered piles.

The ties are located 4 feet below Telegraph Road roadway. The interior arch ribs for both eastbound and westbound bridges share the same interior longitudinal foundation tie. The interior longitudinal foundation tie measured 14'-10" by 3'-2" and is reinforced with 102 - # 9 bars. The tie is 232 feet long. The exterior arch ribs are restrained longitudinally by a 7'-4" by 3'-2' foundation tie which is reinforced with 52 - # 9 bars, and transversely by a 8'-6" by 1'-4" foundation tie which is reinforced with 24 - # 9 bars. The exterior longitudinal tie is 289' long.

Erection of the Middle Segment of the Arch Rib

ARCH RIB OPTIMIZATION

A perfect arch would carry only compression under applied dead load. In order to reach the shape of the arch that will result in minimum bending stresses under dead loads, the shape of the ribs was optimized to closely approximate the equilibrium thrust line that corresponds to the applied dead loads. A compound circular curve was chosen to approximate the equilibrium thrust line. Starting from a basic circular profile with constant radius, the bridge was analyzed under dead loads. The equilibrium thrust line was then determined and a compound circular curve was fitted through the thrust lines. The structural model was then re-analyzed with the new shape of the ribs. The iterative process included analyzing the resulting dead loads from the previous analysis to generate a new shape for the ribs. The final shape of the arch ribs was reached when the bending stresses were negligible. This process resulted in light arch ribs and small arch rib deflections under dead load.

WIND ANALYSIS

Detailed wind studies were performed on the dual bridges. The studies included local wind climatology analysis, assessment of aerodynamic stabilities, assessment of wind loading, and assessment of wind-induced hanger vibrations. Historical wind data was obtained from the Detroit Metro Airport in order to determine the minimum design wind speeds.

The hangers of the bridge were examined to determine their potential susceptibility to wake galloping and vortex-shedding. The vortex-induced hanger vibrations were not considered to be of concern. Almost any small amount of damping added to the hangers was sufficient to effectively suppress vortex excitation.

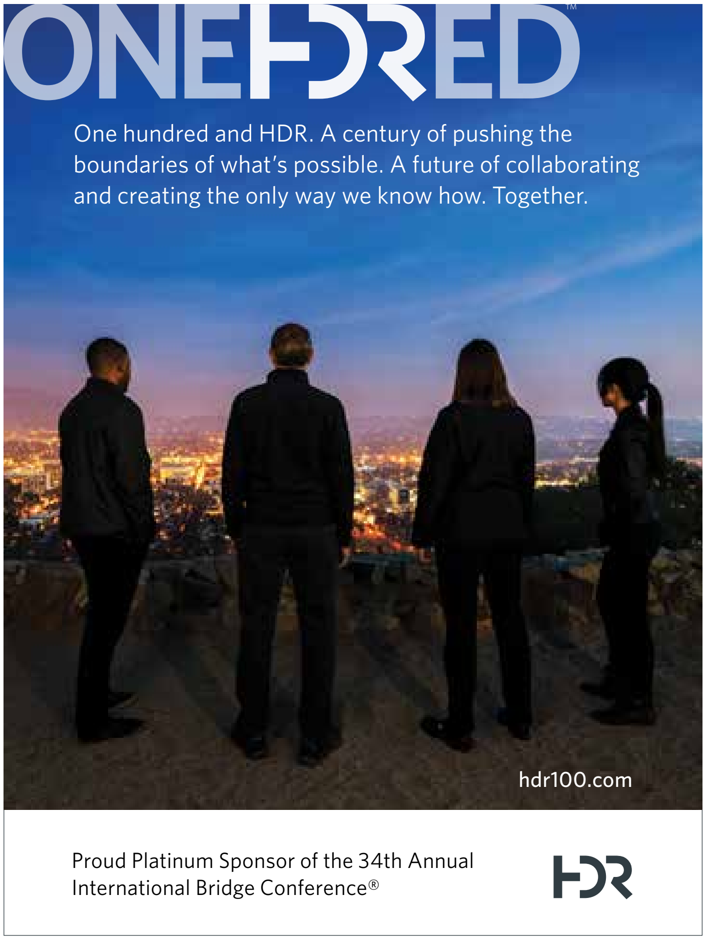
Wake galloping typically occurs at high wind speeds and the expected magnitude of the motion is on the order of the spacing between the adjacent strands. Although the critical wind speed to onset wake galloping is above the wind speeds expected at the site, a hanger separator was installed between the two strands within each hanger assembly for the middle ten hangers. Hanger separators increase the in-plane stiffness of the strands and constrain the relative motions between them.

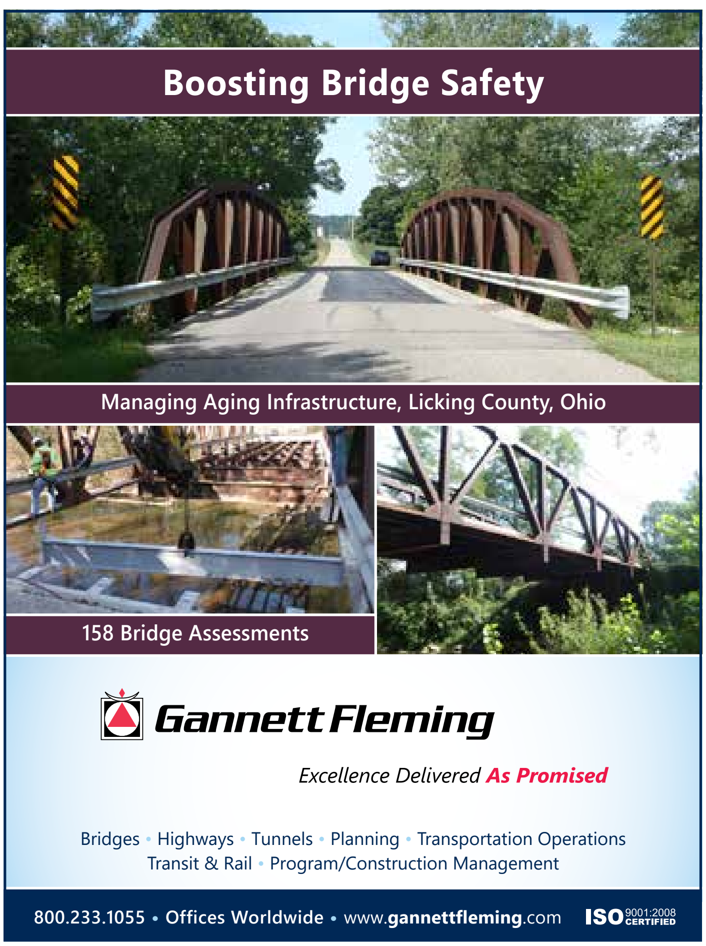
Hanger Separator between the Two Strands

BUCKLING ANALYSIS

Elastic buckling analyses of the bridge was performed to determine the buckling capacity and the allowable design compressive strength of the ribs. Two different buckling analyses were performed. In the first analysis, the structure was modeled with arch ribs only, assuming no contribution from the deck (wet concrete). In this case, the weight of the deck was applied as concentrated loads at hanger locations. In the second analysis, the entire structure was modeled including the deck and hangers to determine the buckling capacity of the ribs due to the stiffness provided by the deck and the hangers. The following are the results of the buckling analyses:

Load Case	Factor of Safety	
	Ribs only	Entire Structure
DL	4.65	8.04
DL+LL	-	6.40
DL+W	-	7.80
DL+LL+0.3W	-	6.30





As noted in the above table for the dead load case, the stiffness provided by the deck and hangers increases the elastic buckling capacity of the ribs by a factor of 1.73.

FABRICATION AND CONSTRUCTION

PDM Bridge in Eau Claire, Wisconsin fabricated the 1.6 million pounds of steel for each bridge. MDOT and Benesch guided the fabrication process, structural details and erection of the bridge.

The original design required shoring during casting of the deck. However, during construction, C.A. Hull, the contractor, chose to cast the concrete deck with the hanger cables carrying the load. With careful management and construction procedures, the deck was cast successfully.

CONCLUSIONS

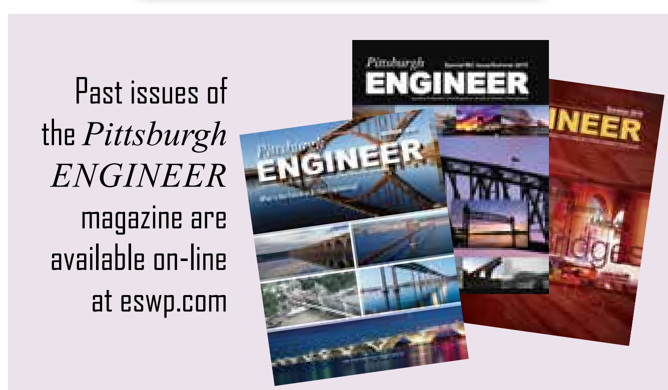
The Gateway Bridge is one of the responses to the efforts of Detroit Regional Gateway Advisory Council (DRGAC) to revitalize Detroit's economy. The local business community and other private sectors have given their support to enhance the I-94 corridor. This structure serves as a gateway to the Metro Airport and a landmark to the city.

The arch bridge with a tied foundation is a unique concept developed by the designers to address the weak soil properties at the site and address the owner desire to avoid the use of a tied arch bridge concept. The concept is cost- effective and addresses the issue of lack or redundancy associated with tied arch bridges.

About the authors...

Muthiah Kasi, PE, SE, CVS is a Chairman Emeritus for Alfred Benesch & Co. He is an internationally recognized contributor in the fields of value engineering (VE) and life cycle cost analysis. With over 46 years of experience, he has led or participated in more than 200 VE studies worldwide. Mr. Kasi has also received many awards for his work in VE, including the "Richard DeMars Special Recognition Award" for his outstanding applications of VE to the design and construction industry.

Ihab Darwish, PhD., PE, SE is a Senior Project Manager for Alfred Benesch & Co. in the East Lansing, Michigan Division. He has more than 20 years of experience in bridge design, construction rehabilitation, inspection and load rating of bridges. His projects won awards from PCI, NSBA, Structural Engineering Association of Illinois and National ACEC.



KENTUCKY'S LAKE BRIDGES:

BASKET-HANDLE TIED ARCHES

by Jason Stith & Gregory Stiles

The Kentucky Transportation Cabinet (KYTC) has nearly completed delivery of the Lake Bridges Project. Construction includes two arch bridges over Kentucky Lake and Lake Barkley as 'gateways' into the Land Between the Lakes National Recreational Area. The twin basket-handled networked tied arches crown the navigable Tennessee and Cumberland River channels. These new US68/KY80 four-lane bridges with a multi-use path stand as fulfillment of KYTC's commitment to improve safety, enhance transportation and promote economic development in western Kentucky.

For the preliminary engineering/planning phase, the two bridges were developed in parallel, engaging the public during Bridge Type Selection. One of the early project goals was to create a visual openness for the structure affording views of the vast lakes and woodlands from their unique vantage points. The 15° inclination gives the arches their basket-handled appearance and creates an openness for both passenger and pedestrian. Structural analysis demonstrated the minimal effect this had on the stiffness or stability of the overall structure. Vierendeel cross braces with moment connections, rather than pinned X-bracing, offer clean lines overhead, and at the portal, the first cross brace was lifted as high as the structural demands would allow. Vehicular barriers were also designed to open up the view. A combination rail with a low concrete parapet opens to a picket style railing on the outside of the multi-use path. Subtle arch feature lighting and low level path delineation lighting enhance the form at night while preserving the dark night skies.

Kentucky Lake Portal View at Dawn

In the final design phase, the design team used their expertise in both arch bridge design and bridge inspection to establish criteria that would facilitate fabrication, simplify erection, and provide safe inspection access. The bridge is designed for rope climbing inspection access. At 110-foot high and 550-foot long and using plates limited to 2-inches thick and 4-feet wide, the arch ribs required refined methods for design and analysis, but were simple to fabricate and their 'I'-shape allows for visual inspection of all surfaces.

Site specific and/or extreme load combinations often governed. Both lake bridges have high wind exposure. Kentucky Lake is the largest reservoir in the eastern U.S., and unobstructed views of the horizon are visible in both directions from roadway deck. A Wind Climate Analysis, Wind Tunnel Testing, and a Buffeting Response Analysis were provided by Rowan Williams Davies & Irwin Inc. The marine site conditions also affected the design. Kentucky Lake is 65 feet deep to the former riverbed, with potential for 90 feet depths when the USACE and TVA hold back flows to reduce flood crests on the Ohio and Mississippi. Frequent barge traffic plie these inland waterways, and a Vessel Collision Report was produced to evaluate risk of collision from an errant barge flotilla. The controlling design vessel was a barge tow with 15 hoppers that measures over 900 feet in length. The waterline footings of the main pier are twelve feet thick and constructed in two lifts above precast soffits and a seal slab.

The Lakes are located just 80 miles to the east of the New Madrid Fault. The US68/KY80 corridor is a designated earthquake evacuation route and KYTC classified both bridges as "Essential" for seismic design considerations. Design seismic ground motion corresponds to a 7% probability of exceedance in 75 years and the Seismic Design Category is 'D' based on the potential for liquefiable soil and lateral spreading, and the 1-second period design spectral accelerations in some areas being greater than 0.50g. To meet the seismic performance objectives, complimentary earthquake-resisting systems (ERS) were developed for the main arch span and the approach girder spans. Lead core elastomeric isolation bearings were designed for the arches, and fluid viscous dampers for the approaches with bi-directional modular joints between the three units. The seismic design effort included time history analyses and required close coordination between Michael Baker (main span), Palmer Engineering (approach spans), and Terracon with Florence and Hutchinson (geotechnical engineering).

A steel box tie girder resists the arch thrust as a tension element. The inclined ribs posed a complex geometric challenge at the intersection of the tie and the rib, known as the knuckle. Finite Element Analyses were used to design this critical region. To facilitate the fabrication of the knuckles, webs of the tie were inclined to match the ribs. This parallelogram box cross section falls outside the assumptions of AASHTO equations, and was analyzed using

Kentucky Lake Arch Lift

a compatibility analysis to demonstrate the tie girder has sufficient capacity even during a hypothetical plate fracture or sudden loss of hanger. Both durability and longevity are enhanced by the use of internal redundancy in design, bolting rather than welding in the build up of the box component plates, and with the use of painted high performance weathering steel plate material.

For the construction phase the two bridges were packaged separately and let one year apart "due to the overall cost and the need to manage cash flow by the Transportation Cabinet" says KYTC's Project Manager, now Chief District One Engineer, Michael P. McGregor, P.E. "Also, there was some consideration to having multiple 'smaller' contracts thus opening the door for more Contractors to participate." A $24.2M advance construction contract was awarded in early 2013 to Jim Smith Contracting. Then KYTC awarded Kentucky Lake Bridge to Johnson Bros for $132M in February 2014 and Lake Barkley Bridge to PCL Civil Constructors for $128M in February 2015.

Although the bridges are nearly identical above the waterline for maintenance considerations, the subsurface conditions between the two lake bridge sites varies significantly. Kentucky Lake's foundations are groups of 2-inch thick, 6-foot diameter driven steel pipe piles with restrictor grillage which formed plugs during driving to engage end bearing resistance. The longest piles are imbedded 130-feet into the gravelly alluvial deposits at the Tennessee River Valley site. Johnson Bros needed two ringer cranes just to pick and set the

Kentucky Lake Main Span after Float and Lift

longer piles. The depths through soil to rock are shallower in the Cumberland River Valley, which necessitated drilled shafts for foundations, and the Karstic conditions of the limestone bedrock often required special remediation techniques either to seal the bottom of shafts or to fill voids in the surrounding rock.

The main span arches for both Lake Bridges were erected on a system of barges floating in the lake near the respective shorelines. Once the ribs and tie girder had been fully assembled and most of the floor framing and hangers were installed, two temporary pipe struts and a tower at each quadrant were erected. The arches were floated out to the main span, and then hoisted using strand jacks to an elevation above the piers. Finally the whole barge assembly and arch were pulled laterally into place by winching against the footings. Slowly and carefully the 5 million pound steel frame was set down in its final position.

"The Transportation Cabinet is very pleased with the final look of the bridge." McGregor said recently. "We were striving for a structure that struck a balance between an iconic view and fiscal responsibility. I think our design team hit it out of the park."

Learn more at www.lakebridges.com

About the authors...

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Gregory D. Stiles, P.E. is a Bridge Engineering Manager for Michael Baker International in Asheville, NC. He is the Engineer of Record for the Kentucky Lake Bridge main span design

1st Place: Bridge of Sighs over the River Cam, Cambridge, UK | Photographer: Todd Thompson
"Great composition and colors!... Charming setting!... Reflects the history of the arch bridge!"

This beautiful Neo-Gothic covered bridge crosses the River Cam on the campus of St. John's College Cambridge. The bridge was built in 1831 to connect the original campus to new structures built on the west side of the river to accommodate the increasing student population. The bridge has very little in common with it's namesake in Venice, Italy other than it is covered. The Venetian bridge led to a prison and provided convicts with their last view of Venice resulting in many "sighs". Rumor has it, students named this Cambridge bridge similarly as many pre-exam students were heard "sighing" as they crossed the bridge from their rooms heading to exams in buildings on the east side of the river.

6TH ANNUAL IBC PHOTO CONTEST

The arch bridge, one of the oldest bridge types, has morphed over centuries from small stone and wooden bridges to large and graceful structures made of concrete and steel. Constructed all over the world by many different cultures, these bridges combine efficiency with aesthetics. The beauty of the arch type bridge–both natural and man-made–is certainly captured on the following few pages...enjoy the top ten photographs, as chosen by the IBC Executive Committee, including some of the comments offered by Committee members!

2nd Place: CSX A-Line Bridge over the James River, Richmond, VA
Photographer: Damian Silverstrim
"Fantastic contrast … Great composition … Surreal reality"

3rd Place: RF&P Railroad Bridge over the Rappahannock River, Fredericksburg, VA
Photographer: Damian Silverstrim
"Love the angle and the composition … A great photo"

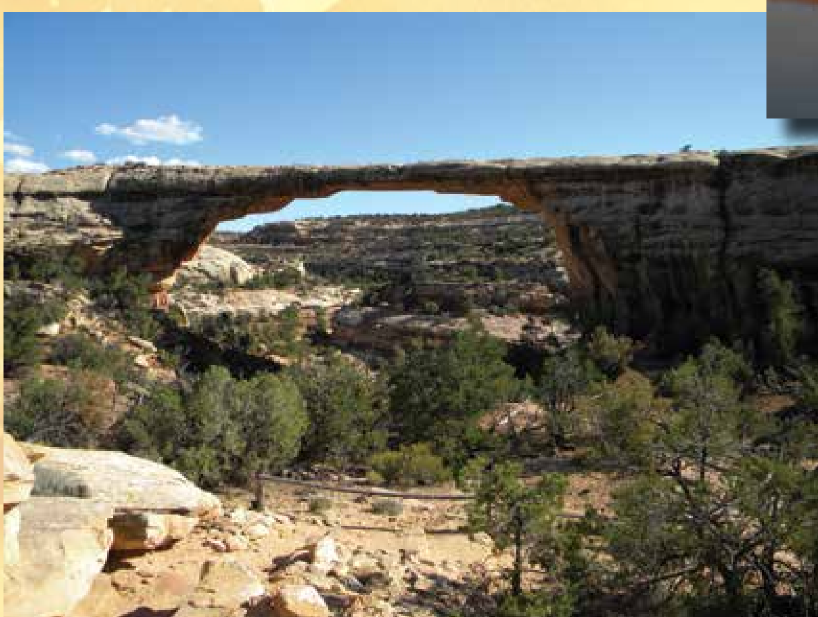
4th Place: Croton Reservoir Dam Bridge over the Croton River, Croton Gorge Park, Croton-on-Hudson, NY
Photographer: Richard Cochrane
"Wonderful capture of light … you can almost hear the roaring Croton River"

5th Place: Yaquina Bay Bridge, Newport, Oregon
Photographer: Warren Kaplan
"Composition and subject matter are *wonderful … Very cohesive photo"*

6th Place: Gapstow Bridge over the Pond, Central Park, New York City, New York
Photographer: Todd Thompson
"Good color contrast ... Striking contrast between the urban city and the park"

7th Place: Mike O'Callaghan-Pat Tillman Memorial Bridge over the Colorado River, Arizona/Nevada Border
Photographer: US Bureau of Reclamation for Federal Highway Administration
"Lots of drama … Excellent composition"

8th Place: Norfolk Southern RR Bridge over the Susquehanna River, Harrisburg, Pennsylvania
Photographer: James Radion
"Peacefulness … Colors and content are striking"



9th Place: Owachomo Bridge, Arches National Park, Utah
Photographer: Stephen Shanley
"Such interesting scenery … One can never cease to be amazed at nature's wonders"

10th Place: Double Arch Natural Bridge, Arches National Park, Utah
Photographer: Stephen Shanley
"Interesting image … Dramatic … Enormity of scale is evidenced by the human reference points"

IBC 2017 AWARDS PROGRAM

By Lisle Williams

"Roebling Winner: "He has been an ambassador for structural engineers during his career … he is an engineer's engineer …"

George S. Richardson Winner: "This work by Professor Connor … will transform how existing and new steel bridges … will be inspected, especially those previously classified as fracture critical members … the end result being a safer bridge inventory, with a better allocation of bridge inspection funds …"

Gustav Lindenthal Winner: "It is a well-balanced structure with elegant span to rise proportioning … the bridge's sleekness is impressive … its design and construction included innovation on many levels and it is one of the finest examples of a bridge blending with its environment that I've seen in a long time …"

Eugene C. Figg, Jr. Winner: "This beautiful bridge is more than just pedestrian-friendly access to a community … the community leaders say: 'the replacement of the Broadway Bridge is a once-in-a-lifetime opportunity to enhance the economic well-being of this community' …"

Arthur C. Hayden Winner: "A beautiful artistic expression … the spiraled, nautilus shape and proximity to the Pacific Ocean … merging urban planning and the intricacies of nature …"

Abba G. Lichtenstein Winner: "This revitalization will, through vision and innovation, provide an icon to the community for many years to come … it will be a wonderful gathering place …""

These are some of the many comments of the International Bridge Conference® Award's Committee who viewed, voted and selected this year's winners, as well as the words of the public who strongly support local bridge projects.

The International Bridge Conference in conjunction with *Roads and Bridges* Magazine, *bridge design and engineering* Magazine, Covestro, and TranSystems, annually awards six medals and one student award to recognize individuals and projects of distinction. The medals are named in honor of the distinguished engineers who have significantly impacted the bridge engineering profession worldwide.

Interest in the IBC awards program is quite robust nationwide and internationally. This year the Awards Committee reviewed more than forty nominations for the various bridge metal categories alone, many of which were projects nominated beyond the borders of the United States. After lengthy deliberations, the following individuals and projects were deemed worthy of this year's awards.

JOHN A. ROEBLING MEDAL

The John A. Roebling Medal honors an individual for lifetime achievement in bridge engineering. The International Bridge Conference is pleased to recognize Mr. Vijay Chandra as the 2017 recipient. Mr. Chandra is a private consultant and former senior technical manager for Parsons Brinckerhoff. Mr. Chandra is noted for his innovative work on bridges and signature bridges. His signature bridges include the asymmetrical cable-stayed bridge over the Charles River in Boston, the extradosed St. Croix River Bridge in Minnesota, and the William H. Natcher Bridge in Kentucky as well as the world's first thermoplastic railroad bridge in Fort Eustis, Virginia and the first thermoplastic highway bridge on a secondary road system of the United States in Maine. Other projects of significance include the design-build Cooper River Bridge, construction engineering for the Lions Gate Bridge, design-build Orlando Airport People Mover, consultation to the Central Artery/Tunnel Project, the design build I-10 at Escambia Bay Sunshine Skyway Rehabilitation, and various movable bridges. Mr. Chandra has developed innovative techniques for stay cable anchorage and was instrumental in advancing technology by bringing into the U.S., the ungrouted stay cable system with the "iso-tension" method of stressing cables. Mr. Chandra also has served on the Federal Highway Administration (FHWA) task force on Accelerated Construction Technology Transfer for reducing design-construction periods for major projects. He has published more than 50 articles and papers in a variety of professional and construction publications. Mr. Chandra has chaired the Precast/Prestressed Concrete Institute (PCI) committee on bridges and served as an active member of the PCI committee on transportation and the Post-tensioning Institute committees on bridges and stay cables. He recently was the Project Director in the development of first national design guidelines to promote a uniform approach for Arches, Cable-Stayed and Suspension Bridges which supplement the AASHTO LRFD Bridge Design Specifications.

Vijay Chandra

GEORGE S. RICHARDSON MEDAL

Robert Connor

The George S. Richardson Medal, recognizing a single, recent outstanding achievement in bridge engineering, is presented to Dr. Robert Connor of Lehigh University, recognizing the significant research contribution to the bridge industry as outlined in his report entitled "Member Level Redundancy of Built-up Steel Girders Subjected to Flexure". This research, funded by a Transportation Pooled Fund -Study #TPF-5(253), was led by Dr. Connor and has demonstrated the significant useable strength and fatigue life which remains following the fracture of one element of a multi-element flexure member. Observations of damaged steel bridges in the field and as well as the intuition of many experienced steel designers has supported the notion that damaged bridges with built-up flexural members often have much more strength and residual fatigue strength than current codes recognize. Never the less, these bridges, with built-up components, are often designated as "fracture critical" requiring labor intensive "hands-on" inspections with associated expenses. The research conducted under this study has demonstrated the effectiveness of the individual components, which provide redundancy in the built-up structural members. This study will likely lead to reclassifications, avoiding "fracture critical" identification for many situations. This research should also lead to design efficiencies and improved in-service inspections, which will be more cost effective and less intrusive to traffic. In addition to the findings alone, the research approach is noteworthy and includes innovative testing and analyses.

GUSTAV LINDENTHAL MEDAL

The Gustav Lindentahl Medal, recognizing an outstanding structure that is also aesthetically and environmental pleasing, is presented to the ADIF Alta Velocidad, the owner of the Viaduct over the Almonte River, at the Alcántara Reservoir in the western region of Cáceres, Spain. The magnificent viaduct is part of a 218 mph high-speed rail line, proposed to connect the two European capitals of Madrid, Spain and Lisbon, Portugal. The viaduct's signature feature is a concrete arch with a main span of 1,260 feet, the third largest concrete arch in the world. The project faced very rigorous dynamic, serviceability and safety criteria, involving complex material and geometrical nonlinear analysis. Nevertheless, it is a slender bridge with a well-investigated shape bearing excellent aerodynamic behavior. The uniqueness of the bridge includes a partially, longitudinally split arch, the use of challenging materials, including 11.6 ksi self-consolidating concrete, and a complex construction process. The construction was accomplished by use of a temporary cable stayed system, which makes the bridge the longest concrete arch in the world erected with this method. Da Vinci was certainly correct when he observed, at the height of the Renaissance, that an arch is "Two weaknesses, that leaning against each other, make a strength."

EUGENE C. FIGG, JR. MEDAL

The Eugene C. Figg, Jr. Medal for Signature Bridges, recognizing a single recent outstanding achievement for bridge engineering, which is considered an icon to the community for which it is designed, is presented to the Arkansas State Highway and Transportation Department, the owner of the Broadway Bridge spanning the Arkansas River and connecting the communities of Little Rock and North Little Rock. With a desire to replace the structurally deficient span of US 70 over the Arkansas River, the community vision for a replacement bridge, that included pedestrian/bicycle facilities, accommodations for a future streetcar line and an iconic design, were met with twin - basket handle arches, each with a span of 440 feet. Accelerated bridge construction (ABC) methods were employed for erection, as each of the two-2,000 ton arches were floated to the site and then hoisted into position. The resulting basket-handle arch bridge not only provides a signature iconic structure that pays tribute to those who served America, but also increases the pedestrian capacity and safety to the traveling public, pedestrians and cyclists. To increase safety to the traveling public, a 16-foot shared-use pedestrian and bicycle path was provided. In addition, to further enhance the trail system, two new pedestrian-only ramps were added that connect the trails on each shore directly to the shared-use path on the bridge. To further enhance the pedestrian experience and attract interest, plaques of each of the 50 states and flags line the river spans, pedestrian walkways.

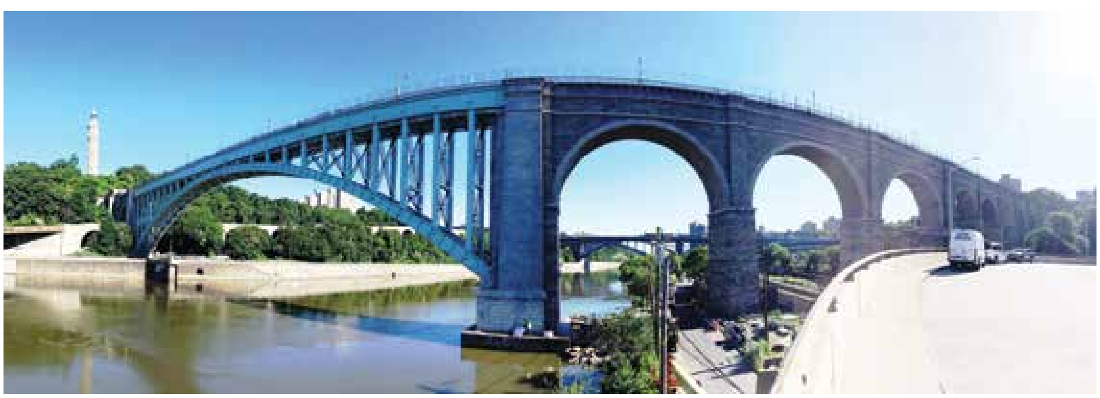
ARTHUR C. HAYDEN MEDAL

The Arthur C. Hayden Medal, recognizing a single recent outstanding achievement in bridge engineering demonstrating vision and innovation in special use bridges, is presented to the City of Santa Monica, the owner of the Idaho Avenue Pedestrian Overcrossing, a 570-foot long post-tensioned concrete slab bridge, spanning the California Incline (roadway), in Santa Monica, California. The Idaho Trail descends from Pacific Palisades Park, a 140 foot bluff above the Pacific Ocean. As a part of the trail, the pedestrian bridge design represents an innovative, context-sensi-

tive design solution that was tailored specifically around numerous site constraints. Specific challenges included working with an existing trail with a steep 10% grade, space imitations over the California Incline, steep, erodible cliffs, and a large elevation drop between the Idaho Trail and Pacific Coast Highway at the base of the bluff. The aesthetic, sculpted profile of the Idaho Avenue Pedestrian Overcrossing resembles a nautilus shell, emphasizing the bridge's connection to the nearby Pacific Ocean. The primary architectural feature, the curved V-pier on the west side of the roadway, was designed to provide a "window" to views of the Santa Monica Pier and the Pacific Ocean. Views of the ocean from the bridge are stunning.

ABBA G. LICHTENSTEIN MEDAL

The Abba G. Lichtenstein Medal, recognizing a recent outstanding achievement in bridge engineering demonstrating artistic merit and innovation in the restoration and rehabilitation of bridges of historic or engineering significance, is presented to the New York City Department of Design and Construction, the owner



of the Revitalization of New York City's High Bridge. The High Bridge is the oldest standing bridge in New York City, dating to its initial construction as a series of stone (masonry) arches across the Harlem River in 1848. Initially known as the Croton Aqueduct, the bridge served for decades as New York City's primary water supply conduit and after 1864, the bridge became a major pedestrian crossing of the Harlem River between Manhattan and the Bronx. The masonry river spans were replaced with a single span steel fixed arch in 1927. The structure was designated a New York City landmark in 1970, and in the same year it was closed to the public. The bridge was listed on the National Register of Historic Places in 1972. The revitalization effort included preservation of the original, under deck, water distribution pipe made accessible for future visitors as a living classroom, installation of reinforcements to the remaining approach stone arches dating from the original 1848 construction, de-leading of the steel arch, cleaning and repointing of the masonry arches, and a transformation of the deck to a public space by installation of brick paving, public bench seating, period lamp posts and other aesthetic improvements such as medallions embedded in the walking surface. The Revitalized High Bridge stands as a proud example of historic structure transformation and urban revitalization on a grand scale, providing a thriving new public use space and interactive visitor destination, 365 days a year for city residents and tourists alike.

THE JAMES D. COOPER STUDENT AWARD

The James D. Cooper Student Award recognizes undergraduate and graduate students who demonstrate an interest and passion for bridge engineering. The award is presented to winners of a student completion for technical writing and engineering insight. The 2017 award is presented to principal author, Mr. Suliman A. Gargoum for a paper entitled: "Automated Network-Level Assessment of Bridge Clearance on Highways Using Mobile LiDAR Data". Mr. Suliman and co-authors Amanda Gadowski, Kenneth Froese, and Karim El-Basyouny (faculty advisor, University of Alberta, Edmonton) present a sensing technique based on LiDAR, to measure the clearance of highway bridges. As LiDAR is a non-contact sensor, the measuring technique is safe and does not interfere with the traffic. The procedure is presented in its generality, and applied to several in-field case studies.

Editors Note:
The IBC Awards Committee includes Lisle Williams, Bill Wilson, Helena Russel, Richard Connors, Gary Runco, Myint Lwin, John Dietrick, Ken Wright, Jay Rohleder, Matthew Bunner, George Horas, Tom Vena, Rachael Stiffler, Shane Baebes, Pat Kane and Tom Leech. The IBC Student Paper Awards Committee is led by Dr. Matteo Pozzi, of Carnegie Mellon University.

About the author...
Lisle Williams, P.E., PLS. is an Honorary Member of IBC and for many years has faithfully served on the IBC Executive Committee, as past General Chairman, Awards Committee, and Roebling Award Subcommittee Chair. In addition, Lisle has served the IBC Executive committee faithfully in many other important roles for the past several decades. – Editor

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