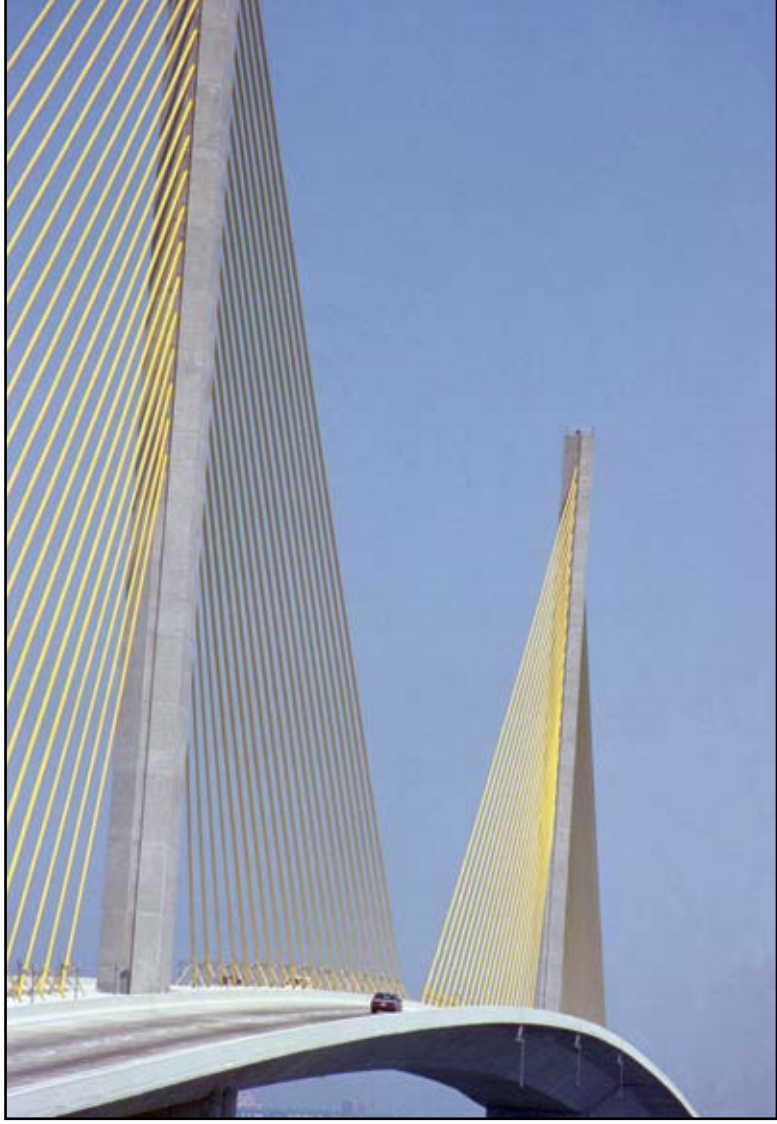
Evolution of Cable Stayed Bridge Technology

By W. Denney Pate, P.E., and W. Jay Rohleder, Jr., P.E., S.E.

Cable-stayed bridges have been compared to the masts of majestic sailing ships, proclaimed as monuments and recognized as engineering marvels. Over the past 30 years, FIGG has designed, studied or provided construction engineering inspection services on over 30 cable-stayed bridges; nine of them have been constructed in the USA and are listed in *Table 1*. Each is a unique structure, designed to address specific transportation functional needs and respond to site, owner and community considerations.

Construction technology and material science for bridges have been an important part of advancing cable stayed bridge technology. Material advancements introduced into bridge applications include self-consolidating concrete, stainless steel, higher strength concretes and composite fibers. New sensor and data communication technologies allow for real time monitoring of bridge information. This data will contribute to refining technologies and lead to the next chapter in state-of-the-art bridge designs. Materials and technology incorporated into bridge designs over the past 30 years have incrementally improved with more economical, sustainable and lower maintenance materials. Over time, technology has also changed the way bridges are designed, with enhancements in software and hardware to model structural behavior, refine elements of the design and produce final designs more quickly.

The cable-stayed bridges described here illustrate some of the advancements in materials and structural components for cable-stayed bridges.



I-275 Bob Graham Sunshine Skyway Bridge, Florida. Recognized by Roads & Bridges magazine in May, 2006 as one of the Top 25 Bridges of all time.

Table 1: Selected cable-stayed bridges in the USA (1987-2007).

Bridge Name	Location	Owner	Main span Length	Date Open to Traffic
I-275 Bob Graham Sunshine Skyway Bridge	Tampa Bay, Florida	Florida DOT	1,200’	1987
I-295 Varina-Enon Bridge over James River	Richmond, Virginia	Virginia DOT	630’	1990
Veterans Memorial Bridge	Port Arthur, Texas	Texas DOT	640’	1990
Cochrane/ Africatown USA Bridge	Mobile, Alabama	Alabama DOT	780’	1991
Clark Bridge	Alton, Illinois	Illinois DOT	756’	1994
Senator William V. Roth, Jr. Bridge over Chesapeake & Delaware Canal	St. Georges, Delaware	Delaware DOT	750’	1995
Leonard P. Zakim Bunker Hill Bridge over Charles River	Boston, Massachusetts	Massachusetts Turnpike Authority	745’	2002
Penobscot Narrows Bridge & Observatory	Near Bucksport, Maine	Maine DOT	1,161’	2006
I-280 Veterans’ Glass City Skyway over Maumee River	Toledo, Ohio	Ohio DOT	Twin 612’	2007

I-275 Bob Graham Sunshine Skyway Bridge, Florida

Florida Department of Transportation

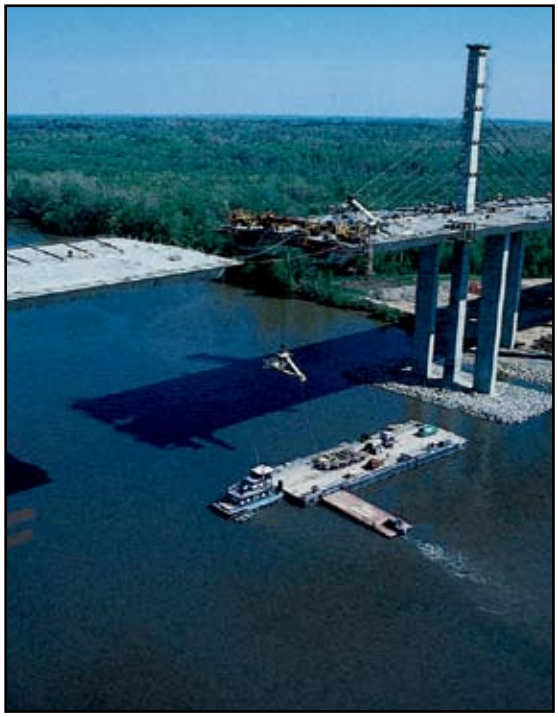
Opened to traffic April 30, 1987, this was the first concrete segmental cable-stayed bridge in America and features a 1,200-foot long precast main span, a single plane of stays and single pylons with twin wall piers. This structure replaced the earlier Skyway, which was destroyed in 1980 by a ship collision. This was one of the first major American bridges designed using guidelines being developed at that time to resist ship impact. Based on the typical ship traffic that travels under this bridge, the two main pylons were designed to withstand a 12 million pound ship impact force.

The new Sunshine Skyway Bridge provides 175 feet of vertical clearance and was designed to withstand wind gusts up to 240 mph, stronger than a Category Five hurricane. New cable stay technology introduced to the United States with this bridge included precast concrete box girder segments with a plane of stays curving continuously through the pylon tower using individual stay pipe saddles. The main span segments are 95 feet wide and weigh up to 220 tons, both records at the time of construction. Each pylon carries 21 stays, anchored at symmetrical locations in the bridge deck at approximately 24-foot centers. The stays range from 38 to 82 seven-wire strands and are encased in steel pipe, with grout injection and precompression within the pipe for additional strand protection. The bridge was designed such that any cable could be replaced individually, if needed during future maintenance. The system provided a strong bridge that could be built quickly. From the time the first stay was installed until closing, the 1,200-foot main span took 10 months. The new Sunshine Skyway introduced many innovations for cable-stayed bridges and has become a structural icon in Florida.

I-295 Varina-Enon Bridge, Virginia

Virginia Department of Transportation

It was originally thought that cable-stayed bridges could only be cost effective in long spans similar to the Sunshine Skyway Bridge. However, with further development of precast bridge technology and the creative application of new shapes, this changed with the I-295 Varina–Enon Bridge, which was completed in July 1990. With a 630-



I-295 Varina - Enon Bridge, Virginia. First use of precast concrete delta frames, proving that cable-stayed designs were cost effective for a moderate span length (630').

SR 1 Senator William V. Roth, Jr. Bridge (Chesapeake & Delaware Canal Bridge) Delaware. Aesthetic lighting highlights the shapes of the bridge at night.

foot cable-stayed main span, the first use of precast concrete delta frames connected to twin box girders and, using a single plane of stays, provided a cost-effective solution for a moderate span length. This bridge carries six lanes of I-295 over the James River, southeast of Richmond, Virginia. At $34.4 million, the bridge was approximately $10 million below the estimate at the time of the bid. At bid, all seven contractors selected the concrete segmental design over a steel design. With precast concrete elements for the piers, superstructure box girders, pylon towers above the deck level and delta frames, construction focused on pre-fabrication and speed of erection. On August 6, 1993, the Varina-Enon Bridge stood strong against a direct tornado strike across the main span without any damage, even with 18-wheel trucks overturned and plowed against the railing…a testament to the strength and torsional stability of concrete cable-stay bridges.

Precast delta frames allow the same size superstructure box girder used in the approaches to be used for the cable-stayed main span, a clear advantage. The 4,680-foot long bridge used the same repetitive shapes throughout. The delta frames connect parallel boxes and encase the cable stay anchorages along the median of the bridge. The cable-stayed main span provides 147 feet of vertical navigation clearance and is supported by 300-foot tall pylons that carry 13 cable stays. Cable stays range in size from 82 to 90 strands, with the cables encased in a polyethylene pipe that is injected with grout around the strands for added protection.

Veterans Memorial Bridge, Texas

Texas Department of Transportation

The Veterans Memorial Bridge was the first cable-stayed bridge built in Texas when it was completed in September 1990. A precast concrete cable-stayed alternate was pre-approved before the bid. This contractor alternate competed against already prepared plans for a steel truss bridge. Since the bridge would only carry one-way traffic, the economical and functional solution was to use twin planes of stays. To speed construction, the four pylons used precast assembly and pre-assembly of each stay as a unit. An entire stay assembly was completed on the deck with a special stay saddle, and then lifted as a single unit into final position on the pylon as precast concrete pylon segments were installed in sequence. A custom-shaped closed cell box girder was created, built using cantilever construction over the water concurrently while the pylons were built. This optimized construction operations. This 1,480-foot long precast segmental bridge features a 640-foot cable-stayed main span, two 280-foot flanking spans, two 140-foot side spans and parallel stays. The creative shapes and assembly methods brought economy to a cable-stayed bridge for a medium span range.

Clark Bridge, Illinois

Illinois Department of Transportation

The 4,620-foot Clark Bridge includes a unique 756-foot cable-stayed main span crossing the Mississippi River. FIGG worked in partnership with another engineering firm to develop the design of this landmark bridge. This cable-stayed design features the first use in the United States of a single pylon with two planes of stays. The 1,360-foot main span unit (302 feet, 756 feet, 302 feet) is supported by the innovation of a cable stay saddle system located over the top of each pylon. Each 252-foot tall concrete pylon carries 44 cable stays that support the main span unit. A bedding plate at the top of each pylon supports the cable stays, which are arranged in two planes that anchor at edge beams along the deck. The introduction of these special design features into the Clark Bridge reduced the number of cable stay anchorages by half, and placed all the cable stressing at deck level to optimize the cable stay cost and labor.

Senator William V. Roth, Jr. Bridge, Delaware

Delaware Department of Transportation

Dedicated in 1995, the SR1 bridge over the Chesapeake & Delaware Canal was the first concrete cable-stayed bridge in the northeast United States. The cable-stayed design, at $58 million, saved the Delaware Department of Transportation $6.2 million against an alternate design. The 3,900-foot long approaches were built using twin precast box girders to build 26 150-foot spans in span-by-span construction. This repetitive superstructure system was used all the way to the pylon. At the pylon, the 750-foot main span was built in one directional cantilever (half from each pylon) using the same box girder from the approaches and adding precast delta frames at each stay location. Each cable stay and 20 feet of superstructure were typically built in four days. The piers are precast box girders, allowing 65-foot tall piers to be built in a single day. The technology of this bridge served as an introduction for more concrete cable-stayed bridges in the northeast United States.

continued on page 14

SR 1 Senator William V. Roth, Jr. Bridge (Cheasapeake & Delaware Canal Bridge) Delaware. The first cable-stayed bridge in the northeast United States opened to traffic in 1995 with a main span of 750'.

Congratulations Minnesota Department of Transportation

ON YOUR NEW I-35W BRIDGE

The new I-35W Bridge was designed and constructed in just 11 months.
The 120 precast concrete segments in the 504'main span were installed in only 47 days.

New I-35W Bridge book!

Opening day commemorative edition includes:

Limited edition photograph of completed bridge

Nearly 200 dynamic, full-color photos

Smart bridge technology & sustainable design

Step-by-step overview of I-35W design & construction

$20* plus shipping & handling
To order call 1.800.358.3444 (FIGG)
or visit www.figgbridge.com

*All book proceeds benefit the Admission Possible program, which makes college admission possible for promising low-income students in the Greater Twin Cities, & through the ACE Mentor Program, will fund new college scholarships for Admission Possible students who want to pursue construction & engineering careers.

FIGG®

CREATING BRIDGES AS ART®

I-280 Veterans' Glass City Skyway, Ohio. The first installation of the cable-stayed cradle system and the first use of stainless steel for cable sheathing. The bridge also utilizes glass and LED lights to create a dramatic signature on Toledo's night sky. Four stays each use 156 strands - the largest by more than 70% on any cable-stayed bridge. The bridge opened to traffic in June of 2007.

Leonard P. Zakim Bunker Hill Bridge, Massachusetts

Massachusetts Turnpike Authority

Crossing the Charles River in Boston is the widest cable-stayed bridge in the world, at 183 feet. The cable arrangement of twin planes in the main span, and a single plane in the back span, provides both the necessary engineering design and an aesthetically pleasing solution. The bridge is asymmetrical both longitudinally and transversely, with the south back span at 282 feet in length and the north back span at 420 feet. Both back spans consist of multi-cell post-tensioned concrete box girders, while the cable-stayed main span is structural steel with a precast concrete deck. The initial design concept was developed by Dr. Christian Menn, with FIGG completing the final design in partnership with another firm. The shape of the pylon, an inverted "Y", creates an ideal way to handle a wide deck with the single and double stay arrangement. The cables are spaced at 20 feet on center in the main span and 15 feet on center in the back spans.

I-280 Veterans' Glass City Skyway, Ohio

Ohio Department of Transportation

Rising high over the Maumee River in the heart of Toledo, Ohio, this cable-stayed interstate bridge opened to traffic in June 2007. The new bridge replaced one of the few bascule spans on the interstate system and created a new landmark for the community. The community chose a theme of 'glass' for their new bridge to celebrate Toledo's heritage for the glass industry in America. To maximize the opportunity to have glass featured prominently in their new bridge, they selected a single pylon bridge in a community design charette (like a workshop) process. They also selected a single plane of stays, resulting in twin 612.5-foot spans on either side of the single pylon. The top 196 feet of the pylon is faced on all four sides with a custom-developed glass. Programmed LED lighting fixtures behind the glass provide an array of distinctive colors that highlight seasons of the year and holidays.

In order to utilize glass effectively in the pylon, a slender sculpted shape was needed while housing very large stays. This resulted in the invention of the cable-stayed cradle system. By eliminating anchorages in the pylon, individual strands are threaded continuously within each stay from the bridge deck, through the cradle and back to the bridge deck. Pre-testing the system earned approval from FHWA and Ohio Department of Transportation. Then the system was pre-purchased prior to bidding to provide a complete tested system to the contractor before construction. Each strand in the cradle is housed in individual stainless steel sleeves, allowing for the use of much larger stays. The 20 stays on the bridge vary from 82 to 156 strands – an increase of more than 70% over earlier cable-stayed bridges. Since the cradle transmits forces through compression into the pylon and there are no anchorages in the pylon, the pylon size was decreased by approximately one third, reducing construction material costs and operations, while enhancing pylon aesthetics. Stainless steel sheathing was chosen for the cable stay casings – a first for cable-stayed bridges.

Penobscot Narrows Bridge & Observatory, Maine

Maine Department of Transportation

Designed and constructed as an emergency replacement for an aging suspension bridge, the length of this 1,161-foot long cable-stayed main span was derived from eliminating foundations in the water and placing pylons on land at the edges of the Penobscot River. The result is an asymmetrical cable-stayed bridge with spans of 480 feet, 1,161 feet, and 480 feet, constructed in balanced cantilever construction using a single box girder. This allowed the river channel to remain open and construction to continue throughout harsh Maine winters. The bridge was delivered under an innovative owner-facilitated design/build method where the Maine Department of Transportation (Maine DOT) retained control over schedule and budget.

Since the new pylon heights would be about twice as high as the old suspension bridge towers, it was important to find an additional advantage to the new height. The height became an economic benefit by incorporating a three-story glass observatory at the top of the pylon on the side of Fort Knox, an established historic tourism site. The new bridge now serves as a tourist and economic development opportunity, in addition to achieving the needed transportation service. At 420 feet on top of the pylon, this provides the tallest public bridge observatory in the world and attracted more than 72,000 visitors during its inaugural season in 2007.

The 20 cable stays in each pylon vary from 41 to 73 strands. Each strand is continuous from bridge deck, through the FIGG-patented cradle in the pylon and back to the bridge deck. Monostrand stressing of the stays was performed from inside the box girder, simplifying construction. The owner's sensitivity to corrosion, after facing the deterioration of the suspension bridge that was being replaced, encouraged an extra emphasis on incorporating new innovative

Penobscot Narrows Bridge & Observatory, Maine. The world's tallest public bridge observatory is entered from historic Fort Knox through the pylon base. An elevator takes visitors to the three-story glass observatory 420' above the Penobscot River.

cable stay system technology. In response to this interest, each stay is protected within a pipe that is designed to be continuously sealed and injected with dry air to create a corrosive-free atmosphere. This feature also allows any breach in the system to be detected by a change in pressurization. The stay exterior pipe is high-density polyethylene, with color impregnated to provide a consistent appearance over time. A new force monitoring system is installed in each stay to provide regular data for monitoring the bridge performance over the more than 100-year service life. Forces in the cable may be measured and recorded as part of regular bridge inspection from inside the box girder. Shortly after the bridge opened to traffic, two reference strands in each of three stays were removed and replaced with carbon fiber composite strands, as a demonstration project through a partnership of the Maine DOT with FHWA. Monitoring and evaluation of the carbon fiber strand performance will provide feedback on the use of this material for viability on future bridges.

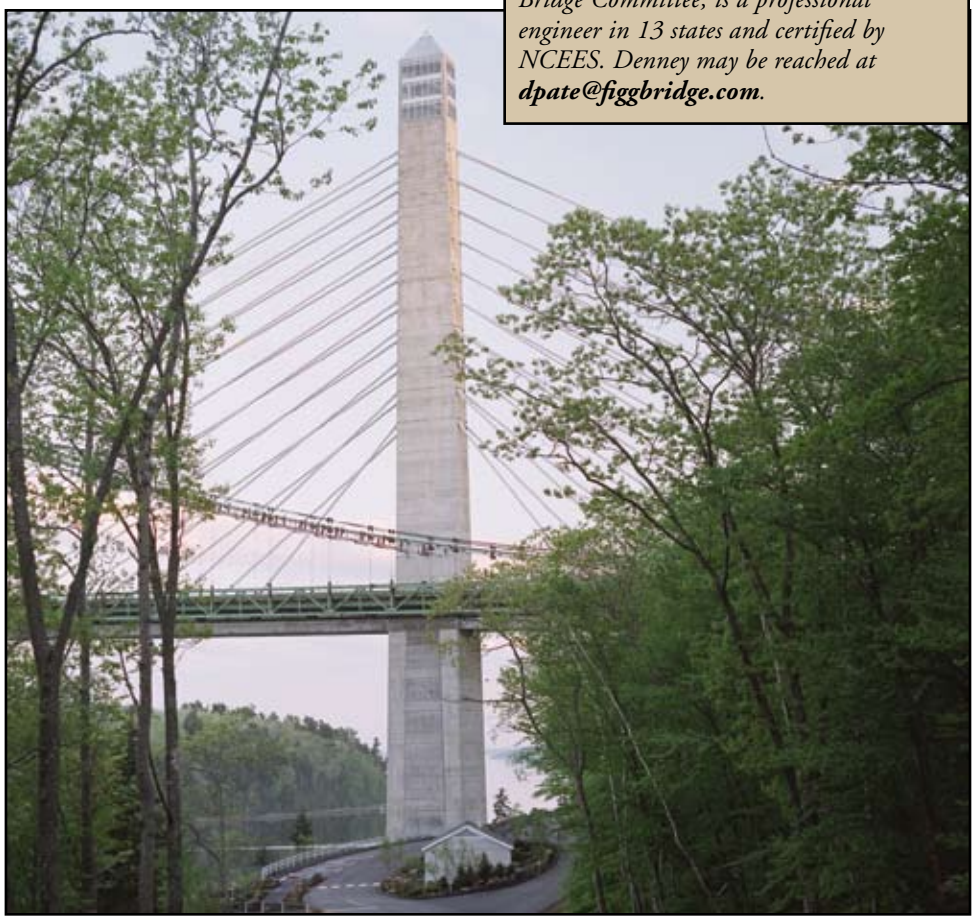
Completed within the $87 million budget, this concrete segmental cable-stayed bridge opened to traffic 42 months after the emergency replacement need was identified. This project represents cable stay technology that helps move the bridge industry forward. (*For more on the Penobscot Narrows Bridge, see STRUCTURE magazine, October 2005.*)

Cable-stayed Bridges for the Future

Cable-stayed bridge technology continues to evolve as new materials are tested and technology continues to advance. Experience from these completed cable-stayed bridges has shown that the torsional rigidity of a closed cell box girder superstructure enhances structural response to wind loading during construction and eliminates the need for temporary stabilization attachments. Unique features such as precast delta frames and struts can expand the box girder to a system that allows the use of single pylons with a single plane of stays. This prefabrication and streamlined approach to long spans contributes to quicker construction. The cable-stayed system of continuous strands, with anchors only at deck level, creates easy access to the stays inside the box girder superstructure for both construction and future inspection. In addition to the economical use of cable-stayed bridges for spans of 600 feet to 1,500 feet and greater, the configurations offer an elegance that also addresses communities' interests in creating exciting landmark bridges for the future.▪

W. Jay Rohleder, Jr., P.E., S.E., is a Senior VP with Bridge Development for FIGG. Jay is registered in ten states, carries NCEES certification and holds an Illinois S.E. registration. Jay is a member of the American Segmental Bridge Institute, the American Society of Civil Engineers and serves on civil engineering advisory boards at Villanova University and Lawrence Technological University. He may be reached at ***jrohleder@figgbridge.com****.*

W. Denney Pate, P.E., is a Senior VP with Principal Bridge Engineer at FIGG. He is credited with the creation of the cradle system. He serves on the PTI Cable Stayed Bridge Committee, the FHWA Virtual Bridge Committee, is a professional engineer in 13 states and certified by NCEES. Denney may be reached at ***dpate@figgbridge.com****.*



Penobscot Narrows Bridge & Observatory, Maine. Maine's first cable stayed bridge opened to traffic on December 30, 2006. It incorporates the cable stayed cradle system for a low maintenance replaceable system. It is the first installation of carbon fiber strands in an American cable-stayed bridge.