TOLEDO'S I-280 VETERANS' GLASS CITY SKYWAY:
A PRECAST CONCRETE LANDMARK BRIDGE

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ABSTRACT

Elevating I-280 high above the Maumee River required approximately 27,000 linear feet of precast concrete segmental construction, including a unique cable-stayed main span unit. The all-concrete solution demonstrates the durability, versatility and aesthetics that may be achieved utilizing concrete. The new bridge, opened to traffic on June 24, 2007, is the single largest project ever undertaken by the Ohio DOT. Concrete with up to 10,000 psi compressive strength has been used to create dramatic structural elements, while reducing size and weight. Concrete has met all of the expectations for color, strength and durability established for this major landmark bridge.

The centerpiece of the new bridge is the 1525 ft cable-stayed main span unit featuring a 400 ft tall single pylon. All four sides of 196 ft of the upper pylon are faced in glass, celebrating Toledo's industrial heritage. 384 LED fixtures behind the glass will allow for more than 16 million color combinations that will light the skyline of the city. A new cradle system for cable stays was developed for this project and offers many benefits for designers and owners.

Keywords: Precast, Segmental, Cable-Stayed, Cradle, Stainless Steel, Bridge Lighting, Post-Tensioning, Cantilever, Span-By-Span, Delta Frame, Glass, LED

INTRODUCTION

The new Veterans' Glass City Skyway carries I-280 across the Maumee River and is the centerpiece of the largest construction project ever undertaken by the Ohio Department of Transportation (ODOT). Opened to traffic on June 24, 2007, this cable-stayed river crossing features two 187 m (612.5 ft) spans flanking a single 133 m (435 ft) tall concrete pylon located in the middle of the Maumee River. The main span unit was constructed completely from the "top-down" using a combination of span-by-span and uni-directional cantilever precast segmental erection techniques. This allowed completely unrestricted shipping access to the Port of Toledo to continue throughout construction of the project.

The stay cable system was the first ever to be designed using the new stay cradle to carry the strands of each stay through the pylon, eliminating the need for stay anchorages to be embedded into the pylon concrete. This allowed FIGG, the Designer of Record for the project, much greater freedom to incorporate aesthetic features into the pylon design that reflected the public's desire for a landmark signature structure. The Veterans' Glass City Skyway Task Force, consisting of citizens, business owners, and project stakeholders in the northwest Ohio area, selected the theme of "Glass" to celebrate Toledo's long heritage in the glassmaking industry. For the first time on any cable-stayed bridge in the world, reflective glass panels were incorporated into all four sides of the upper 60 m (196 ft) of the pylon and highly efficient LED light fixtures were installed to light the pylon in any of 16.7 million colors.

PROJECT OVERVIEW

PROJECT LOCATION

The new Veterans' Glass City Skyway carries Interstate 280 traffic over the Maumee River approximately one mile east of downtown Toledo, Ohio. The Maumee is the largest tributary to the Great Lakes, emptying into the western end of Lake Erie. At the location of the bridge, the river is approximately 1000 feet wide. Because of its size and location, the Maumee serves as access to the Port of Toledo, one of the busiest ports in the Great Lakes shipping system.

Interstate 280 is a heavily traveled truck route and serves as the fastest land connection between the industrialized cities of Cleveland, Ohio and Detroit, Michigan. Approximately 70,000 vehicles use this portion of I-280 each day, with a large percentage of those being trucks involved in interstate commerce.

Prior to the construction of the new bridge, I-280 traffic used the 1950's era Craig Memorial Bridge, one of the last movable bascule bridges on the interstate system in the United States (see Figure 1). It is also one of the most heavily used, with an estimated 900 openings for ships each year. Thus, as early as 1988, the Toledo Metropolitan Area Council of

Governments identified the construction of a new bridge over the Maumee River as its top transportation priority.

Fig. 1 The Craig Memorial Bridge opens to allow passage of a Great Lakes freighter.

MAIN SPAN UNIT

The cable-stayed main-span crosses the Maumee River with two 187 m (612.5 ft) spans that flank the main pylon (see Figure 2). Twenty stay cables in a combined fan/harp arrangement support the precast concrete segments of the superstructure with deck-level anchorages located every 8.53 m (28.0 ft). The stays are aligned in a single plane along the axis of the pylon and pass through the upper pylon at 2.74 m (9.0 ft) intervals. The bridge superstructure provides more than 37.8 m (124 ft) of vertical clearance and much more than the required 61.0 m (200 ft) of horizontal clearance for the existing navigation channel. The main span unit is designed to carry three 3.66 m (12 ft) lanes of highway traffic with two 3.05 m (10 ft) wide shoulders in each direction.

The superstructure is comprised of twin precast segmental trapezoidal box girders. At stay anchorage locations, the two box girders are connected together into a rigid frame using a precast concrete delta frame (see Figure 3). This triangle-shaped element is connected with concrete closure pours and post-tensioning tendons to the adjacent box girders. Along with diagonal concrete struts cast into the adjacent box girder interiors, the delta frames transfer traffic loads from the bridge deck transversely to the centrally-anchored stay cables. A post-tensioned concrete slab is also cast to fill in the deck area between delta frames. The use of delta frames to connect two box girders greatly reduces the size and weight of the precast elements needed to carry six lanes of interstate traffic.

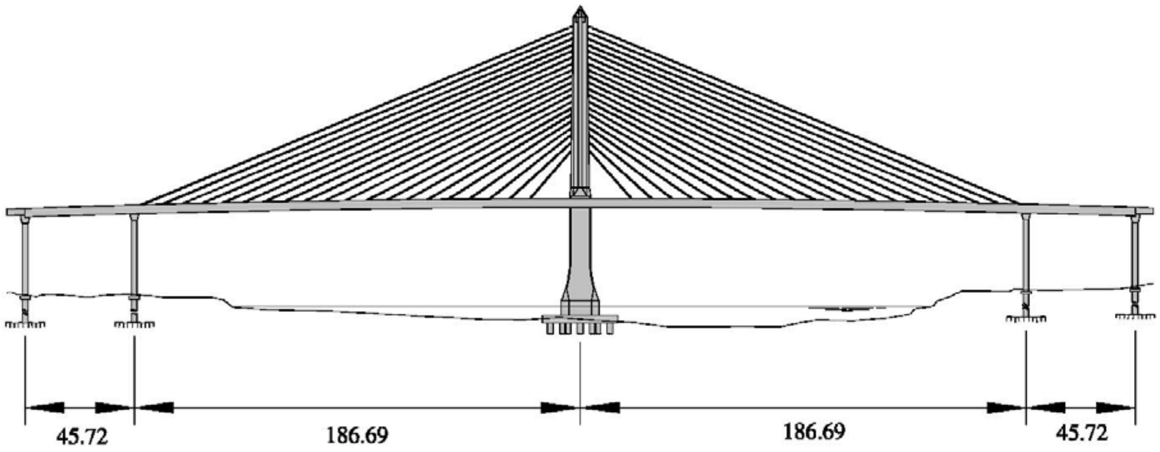

Fig. 2 Elevation view of the main span unit (all units m).

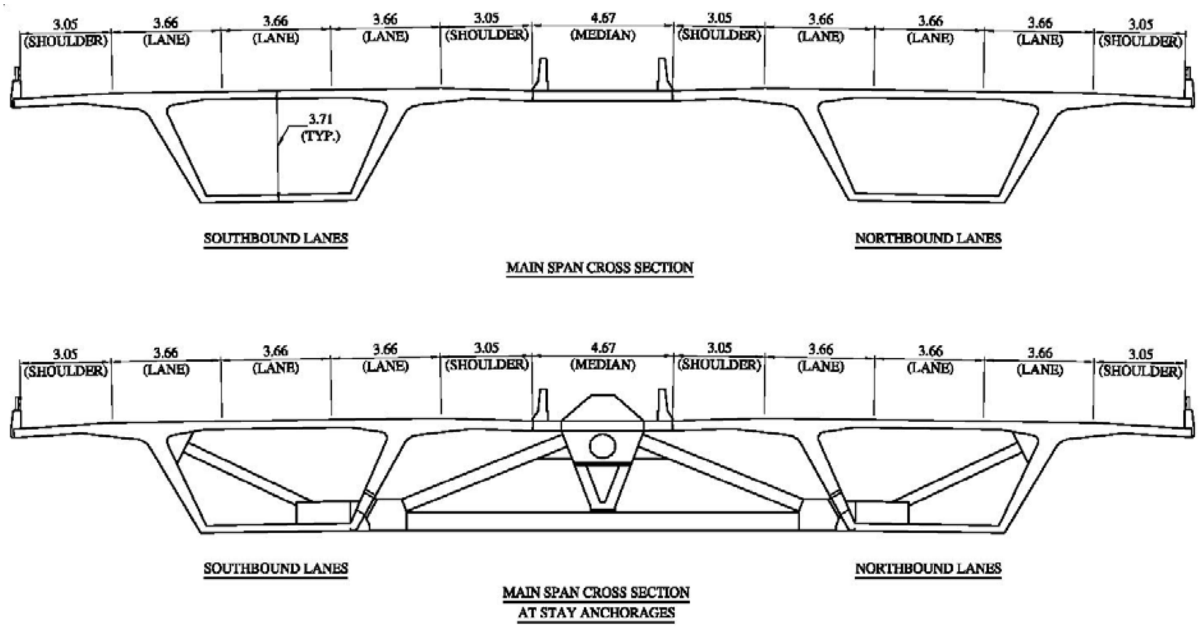

Fig. 3 Main span typical cross-section and cross-section at stay anchorages (all units m).

MAIN PYLON

Figure 4 shows the layout of the main pylon and its cross-sections. The pylon is founded on 17 drilled shafts each with a diameter of 2.44 m (8.0 ft) and socketed 4.6 m (15 ft) into the bedrock below the river. The drilled shafts are connected with a 4.88 m (16.0 ft) thick circular concrete footing with a diameter of 31.70 m (104.0 ft). This footing provides the base upon which the main pylon is founded, and is located approximately 3.0 m (10 ft) below the Maumee River mud line.

The lower portion of the pylon rises 48.4 m (158.7 ft) from the footing to the underside of the bridge superstructure. The first 9.14 m (30 ft) of this height above the top of the footing is a constant, octagonal cross-section. The remainder of the lower pylon has a sculpted appearance with a variable cross-section which is generally rectangular. The exterior dimensions of the lower pylon vary widely. At the base, the cross-section is 15.80 m (51.8 ft) in length and 8.53 m (28.0 ft) wide. Near the roadway level, these dimensions reduced to 8.84 m (29.0 ft) long and 4.06 m (13.25 ft) wide.

The pylon diaphragm is located at the level of the roadway, and frames the continuous superstructure into the pylon. This solid beam has the same general shape as the twin box girders of the bridge superstructure. It provides an anchorage diaphragm for longitudinal post-tensioning tendons running through the superstructure.

The upper portion of the pylon reaches to 80.7 m (264.75 ft) above the level of the roadway. This portion of the pylon also varies in cross-section, but much less dramatically than the lower pylon. The upper pylon has a unique “cruciform”-shaped cross-section that varies from 8.84 m (29.0 ft) to 6.30 m (20.67 ft) in length and has a constant 4.06 m (13.25 ft) width. This cross-sectional shape provides locations for glass panels incorporated into four sides of the pylon. The glass panels and the curved faces of the pylon concrete form four cavities through which maintenance elevators can travel to access the entire height of the upper pylon.

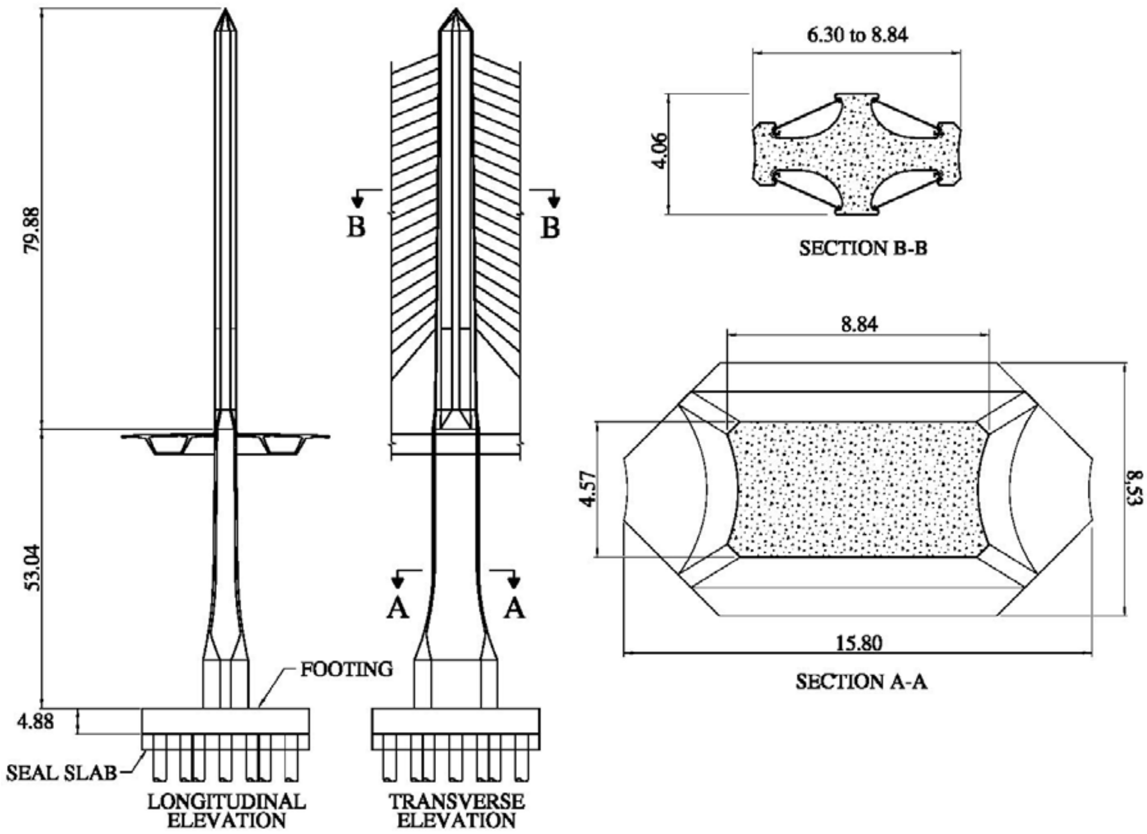

Fig. 4 Elevation and cross-section views of the main pylon (all units m).

MAIN SPAN ERECTION METHOD

Maintaining shipping traffic to and from the Port of Toledo was deemed a top priority during the design phase of the project. The main shipping channel is located just north of the central pylon, and is heavily used during all seasons except winter. This meant that any erection method for the main span unit would need to avoid placement of barges, cranes, or other erection equipment within the limits of the shipping channel.

The alignment of the approach structures leading to the main span unit was almost entirely within the current I-280 right-of-way. In addition, ODOT had made a commitment to the community to avoid extensive lane closures on I-280 during construction and maintain, at all times possible, two lanes of I-280 traffic in both directions. Because of this, FIGG designed the approach spans to be built using the span-by-span method from the top. All precast segments were to be delivered to the erection front using the completed spans of the new structure, rather than driven to the erection truss and lifted from the ground.

For a cable-stayed superstructure with 187 m spans surrounding a single pylon, erection might typically be performed using the balanced-cantilever method, with two cantilevers advancing outward simultaneously from the pylon. However, this would require segments and possibly cranes to be placed on barges in the main shipping channel. Moving this equipment out of the way for Port traffic approximately 900 times per year could adversely impact the construction schedule.

Several of FIGG’s previous cable-stayed bridges had been successfully designed and constructed from the “top-down” with no water access necessary. Of these, the Verina-Enon Bridge in Virginia and the C&D Canal Bridge in Delaware feature a central plane of stays similar to the layout selected as the preferred alternate by the VGCS Task Force.

ERECTION SEQUENCE

The erection sequence shown in the Contract Plans was almost identical to that actually used by the Contractor, Fru-Con Construction Corporation, during work on the Skyway’s main span unit.

The erection of spans in the main span unit began after completion of the southern approach spans using the span-by-span method. Temporary steel truss towers were assembled on temporary footings founded on groups of steel pipe piles. The back span portion of the main span unit was then erected using the span-by-span method from the southern end of the unit northward to the pylon diaphragm. Three pairs of temporary towers were used to support the four temporary spans that would later make up the 187 m long permanently cable-stayed span directly south of the main pylon.

The completed back span portion of the main span unit then provided a route to transport precast segments and delta frames to the main cantilever for erection. As erection of the main cantilever progressed and stay cables began supporting both the main cantilever and the back span, the structural system of the main span unit began to change. The erection sequence included several steps when the temporary towers supporting the back spans were removed. After stay 7 was stressed, temporary tower C was deactivated and disconnected from the superstructure. The same step occurred at tower B after installation and stressing of stay 12. Finally, the last temporary tower A was deactivated upon completion of the final cantilever closure pour and stressing of continuity tendons (see Figures 5a through 5d).

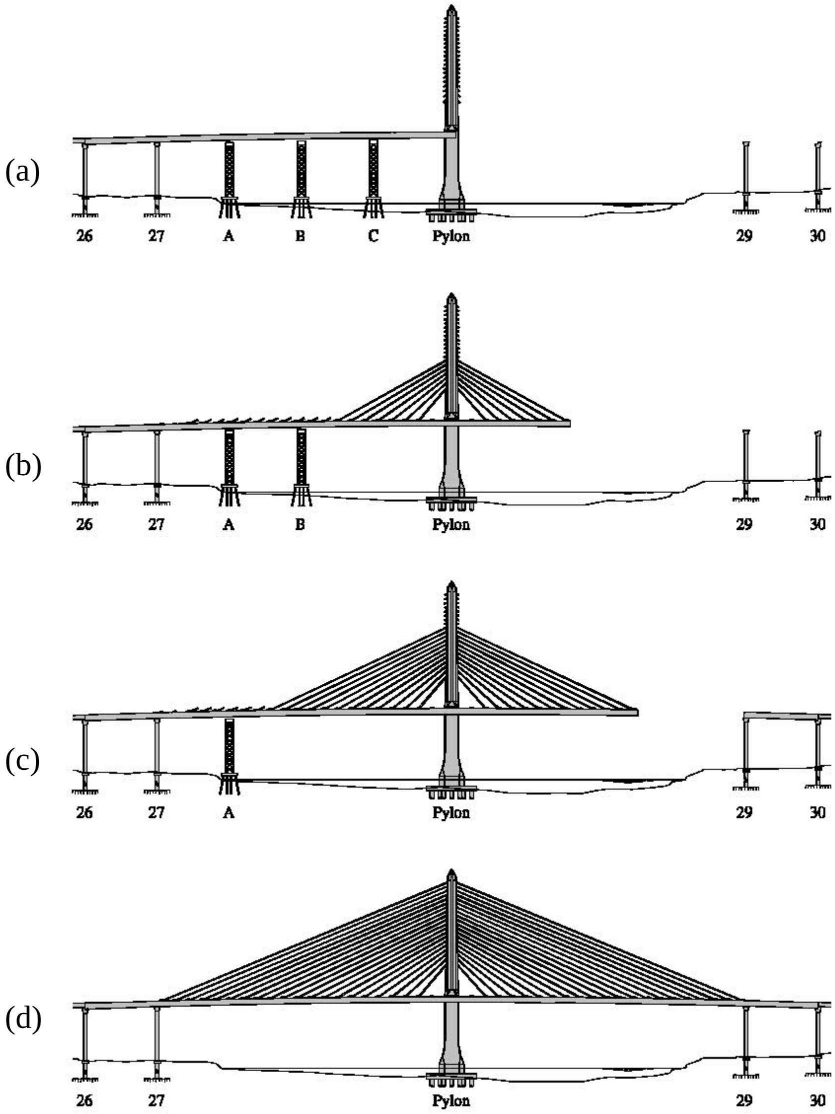

Fig. 5 General sequence of main span erection. (a) Back spans constructed span-by-span on temporary towers, (b) temporary tower “C” removed after stressing stay 7, (c) temporary tower “B” removed after stressing stay 12, (d) temporary tower “A” removed and main span complete after casting final closure at pier 29.

POST-TENSIONING LAYOUT

The change in the static scheme of the main span unit as erection progressed also necessitated changes in the post-tensioning tendon layouts to control axial stresses during construction and provide the proper permanent tendon layout for the bridge in service.

During span-by-span erection of the temporary back spans, the tendon pattern generally consisted of a series of draped external tendons in each span similar to typical span-by-span bridges. As main cantilever erection and stay stressing progressed, the draped tendons were detensioned and removed from the temporary spans in a similar sequence to the removal of the temporary piers. After stressing stay 3, the draped tendons closest to the pylon in temporary span D were removed. Similarly, after completion of stays 8 and 13, the tendons in spans C and B (respectively) were detensioned. Finally, the draped tendons in span A were removed after stressing of stay 18. Just before casting of the final main cantilever closure, a series of partially-draped external tendons passing through spans A, B, and C were stressed. This group, along with internal bottom and top slab continuity tendons in the back span and cantilever span, provided the appropriate tendon layout for the permanent structural configuration during the service life of the bridge.

TYPICAL CANTILEVER ERECTION SEQUENCE

The structural system and layout of the main cantilever was intentionally designed to be as repetitive as possible to simplify the cantilever erection process. Each cycle of segment erection and stay cable installation followed the same basic set of steps.

Upon completion of the previous stay installation and stressing, the first step in the typical cantilever erection cycle was the delivery and erection of six superstructure segments. These segments were arranged in two “mini-cantilevers” of three segments each. The first two pairs were typical segments located between delta frames. The last two segments had blockouts in their web walls into which the lower corners of the precast delta frame fit. The cantilever segments were erected using Demag AC400 hydraulic cranes located on the previously erected segments (see Figure 6). The new segments were delivered to the ends of the cantilevers using special 12-axle hauler trailers.

Epoxy was applied to the face of the new segment prior to lifting it into position. Each segment was post-tensioned to the previous one using a series of 16 ~ 35 mm (1.375 in.) diameter post-tensioned bars. The post-tensioning was sufficient to support the weight of the crane on the mini-cantilever while the delta frame anchor segment was lifted into place. Each typical superstructure segment weighed approximately 800 kN (90 tons). Segment erection in the mini-cantilevers was alternated back and forth between them to ensure that one cantilever was never advanced farther than one segment beyond the other. This balancing of the dead loads reduced the torsional stresses on the completed main cantilever to the extent possible.

Fig. 6 Erection of precast superstructure segments in cantilever.

Immediately after erection of the three-segment mini-cantilevers were completed, the precast delta frame was delivered to the cantilever tip using the same 12-axle hauling trailer and lifted into position using one of the hydraulic cranes (see Figure 7). The second crane was used to complete the installation and alignment of the delta frame’s temporary support beams. Once the weight of the 845 kN (95 ton) delta frame was transferred to the beams it was surveyed and aligned to the proper vertical angle of the stay pipe and the correct position relative to the adjacent superstructure segments. The delta frame was then locked into position with small hydraulic jacks.

Fig. 7 Precast delta frame is lifted into place using a crane on the cantilever tip.

Next, the precast delta frame was connected structurally to the roadway segments. Formwork was installed to cast two small closures where the bottom corners of the delta frame connected to blockouts in the segments' web walls (Figure 8). Also, the median slab between the mini-cantilevers' segment wings and the delta frame's stay anchor head was formed. Rebar and transverse slab tendon ducts were installed (Figure 9). Concrete was placed at these three locations, heated, and cured until it reached a minimum compressive strength of 27.6 MPa (4000 psi). The transverse deck tendons and a 27 strand tendon that anchored near the bottom corner of the delta frame were then stressed to tie all of the elements of the structural system together.

Fig. 8 Forming for the delta frame bottom corner closure pours.

Fig. 9 Formwork, reinforcement, and transverse post-tensioning for the median slab.

Once the post-tensioning was completed the twin box girders, delta frame, and median slab were a complete structural system ready for the installation and stressing of the next stay cable. A work platform was installed at the end of the cantilever to temporarily provide access to the stay anchorage (see Figure 10).

Fig. 10 Stay stressing platform being lifted into place at the end of the main cantilever.

STAY CABLE SYSTEM

GENERAL LAYOUT

The stay cable system for the Veterans' Glass City Skyway incorporates several unique features. The main tensile element consisted of 15 mm (0.6 in.) diameter, epoxy-coated seven-wire strands, varying from 82 to 156 strands per stay. The 156-strand stays represented the largest known stay cables of any bridge in the world.

Each stay's strands ran continuously from deck level anchorage, through the main pylon, and back down to the opposing deck level anchorage (see Figure 11). No stay anchors were located within the pylon itself. This arrangement was made possible through the use of an innovative cradle system that kept all the strands parallel to one another in separate individual steel sheaths as they passed through the pylon. The strands remained parallel to each other throughout the length of the stay into each anchor, and were further protected by a stainless steel outer sheathing. Components of the stay system were supplied by Dywidag Systems International (DSI) as a separate contract to ODOT prior to letting the main bridge contract.

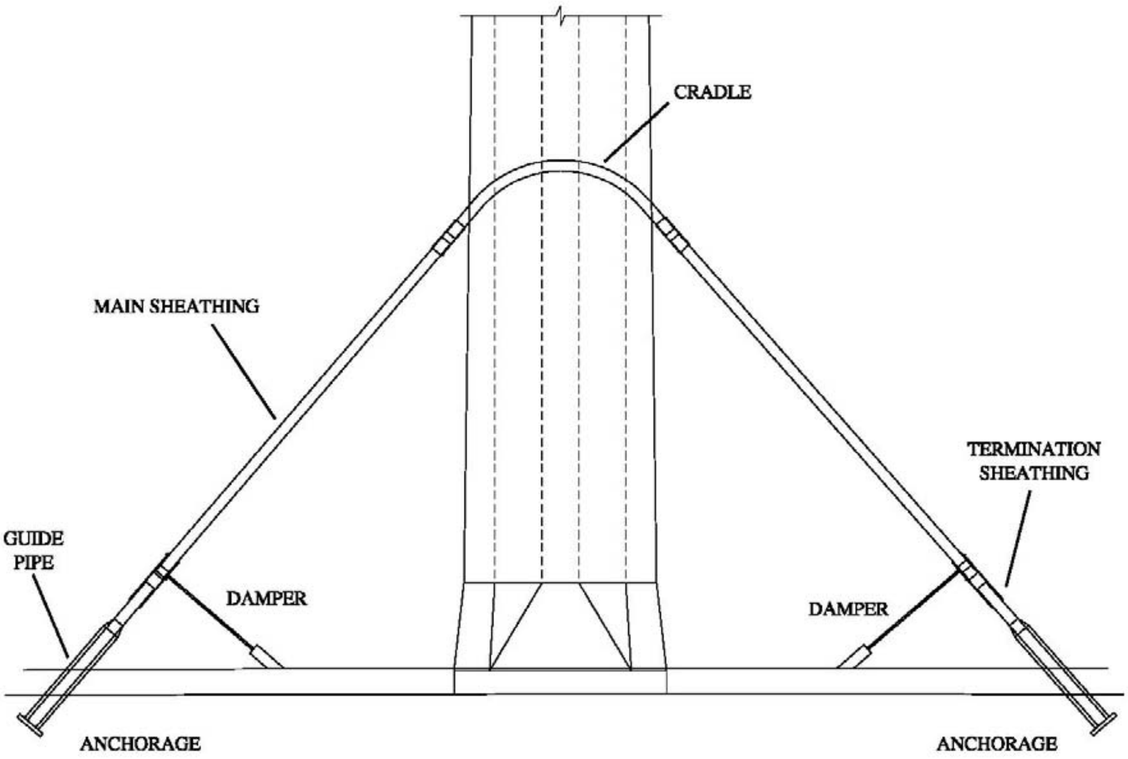

Fig. 11 General layout of stay cable system.

STAY CRADLE SYSTEM

The cable-stay cradle system was developed and patented (U.S. Patent No. 6,880,193) by FIGG during the design phase of the Veterans' Glass City Skyway. The cradle allowed the elimination of stay anchorages in the pylon similar to a curved saddle pipe, while addressing perceived concerns of fretting corrosion due to strand-to-strand interaction that would normally occur in a conventional saddle pipe.

Many modern cable-stayed bridges incorporate stay anchorages in the pylon. However, this requires designers to counteract the high tensile forces generated between these anchors with large amounts of reinforcement and post-tensioning. More recently heavy, complex, and expensive steel anchorage boxes have been embedded in concrete pylons for the same reason. Instead of generating large tensile forces, the cradle system transfers the load of the stay cables to the pylon concrete through direct radial compressive stresses, taking advantage of concrete's inherent ability to efficiently handle large compressive loads (see Figure 12). This more efficient load transfer results in a reduction in reinforcement and cross-sectional area of the pylon concrete.

Because the cradle keeps all of the stay's strands parallel and prevents strand-to-strand contact, it is fully compatible with the monostrand stressing systems that have revolutionized the stay cable installation process in recent years. This effectively removes the limits on stay cable sizes previously imposed by the large size and difficulty of using multistrand jacking systems.

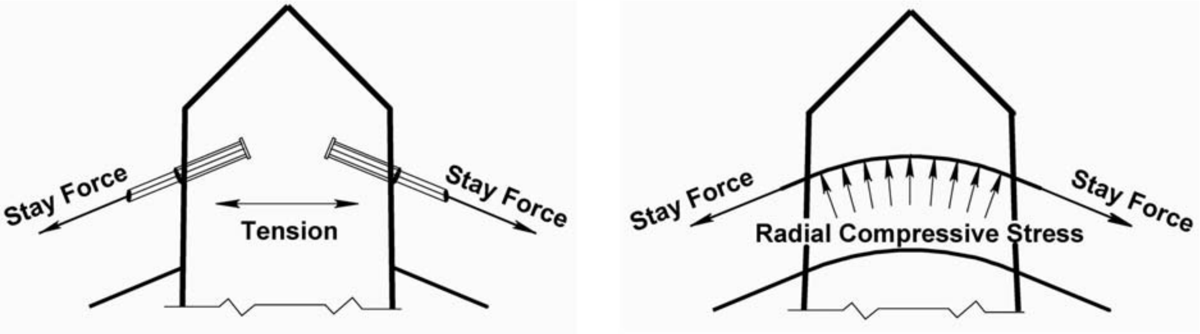

Fig. 12 Transfer of stay forces to pylon using anchorages (left) and stay cradle (right).

The cradle system consisted of an external Grade 316L stainless steel curved pipe. Inside this outer sheathing, a series of individual 25 mm (1 in.) diameter stainless steel tubes carried each of the seven-wire strands of the stay cable's main tensile element. The individual strand sleeves were parallel to each other throughout the length of the cradle pipe, and their ends were flared to avoid damaging the strands' epoxy coating during their installation in the field. "Cheeseplates" were spaced at seven locations along the length of the cradle to guide the sleeves in their proper path. The interstitial space between the individual sleeves was filled with a structural grout with a minimum compressive strength of 34.5 MPa (5000 psi). Rather than corrosion protection, the purpose of this grout was to provide a load transfer path for the radial compressive stresses generated by each individual stay strand as it passed through its curved sleeve inside the cradle.

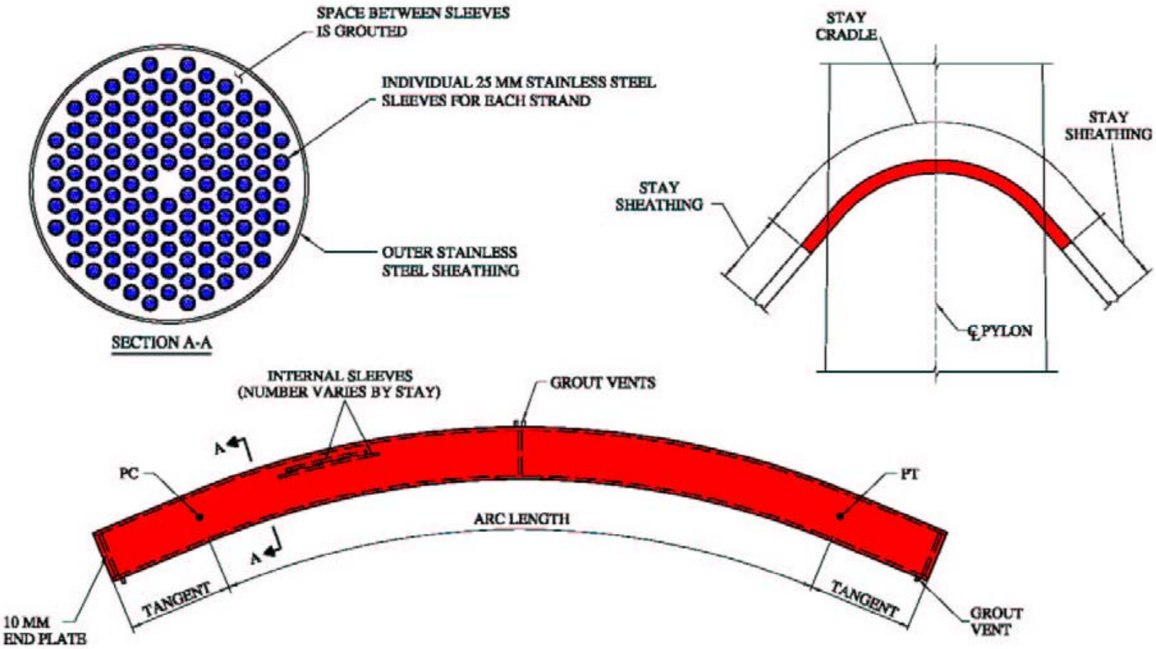

Fig. 13 General layout of stay cradle.

After grouting, the stay cradles weighed approximately 44.5 kN (10 kips) each. Installation and alignment of the cradles, similar to a saddle pipe or a tendon deviator pipe, was relatively straightforward. The cradles were stamped with alignment markings at each end and at the midpoint. The cradles were surveyed, aligned, and adjusted for proper elevation based on the pre-calculated theoretical coordinates for those points. Alignment of the cradle was performed independently of the alignment surveys for the pylon formwork to ensure higher accuracy.

Fru-Con designed a two-part support frame from which the cradle was hung at three points along its length. The frame and cradle were then lifted as a unit and set onto the top concrete surface of the previously cast pylon lift (see Figure 14). The reinforcing steel for the new pylon lift was placed around the cradle. After the forms were closed the upper portion of the cradle support frame was set to bear on the forms, and the load of the cradle was transferred from the lower part of the frame to the upper portion. The lower section of the support frame was then removed to be reused later. The previously open north and south faces of the pylon forming system, where the ends of the cradle penetrated the concrete's surface, were then "stick-built" around the cradle ends.

Fig. 14 A stay cradle and its support frame is set into the pylon formwork by the tower crane.

STAINLESS STEEL SHEATHING

This project was the first use of stainless steel stay cable sheathing in the United States. The sheathing pipe consisted of 4.1 mm and 4.8 mm (0.165 in. and 0.188 in.) thick Grade 316L stainless steel plate rolled into 457 mm and 508 mm (18 in. and 20 in.) outer diameter pipes and welded longitudinally. Stays 1 through 6 used the smaller sheathing, while stays 7 through 20 were 508 mm (20 in.) in diameter. After welding the outer surface of the pipes were ground and polished to a No. 4 surface finish, giving the appearance of a brushed shine without mirroring. The completed sections of pipe were delivered to the project on flatbed trucks in typical lengths of 8.2 m (27 ft). Pipe fabrication was performed by SWEPCO, Clifton, New Jersey and grinding and polishing was done by Custom Manufacturing and Polishing in Springfield, Missouri.

After shipment to the project, the sheathing sections were stored in a climate controlled warehouse along with the other components of the stay cable system. The shipped pipe lengths had to be welded together to make the required sheathing lengths prior to final installation into the bridge structure. Final stay lengths varied from 21 m to 185 m (69 ft to 606 ft), and more than 400 welds were required to assemble all shipped sections into the final stay sheathing. Because the cantilever erection was on the project's critical path, and the typical erection cycle left little time for welding of sheathing sections at the site, Fru-Con elected to use the same warehouse as a weather-protected work environment in which to perform as many welds as possible before main span construction (see Figure 15).

Fru-Con welded the sheathing sections into lengths of approximately 24.7 m (81 ft), the maximum length that could be easily driven from the warehouse to the bridge deck. In this way, approximately two-thirds of all the welds were performed in a protected environment off the project's critical path.

Fig. 15 An orbital welding machine is used to weld stainless steel sheathing sections.

For the remaining welds, a portable welding shack was set up on the completed approach bridge deck south of the main span unit. There, the sheathing sections were surveyed, aligned, and the last remaining welds were completed, ground, and polished. The full-length stay sheathings were then towed on carts along the bridge deck up to the main span.

The stay cable installation subcontractor, Freyssinet, devised an ingenious method for lifting the full length stay sheathing into its final position. A temporary stay cable, called a highline, was anchored in the pylon top and on the north and south shores of the Maumee River. Located periodically along the length of the highline were pulley assemblies. Pulleys were also attached to the bridge deck directly beneath the highline pulleys. A single winch line, starting at a winch located on the bridge deck near the pylon, was threaded up through the first highline pulley, down to the first deck pulley, back up to the highline and the next pulley, and so forth until it traveled through all of the pulleys in the system. When the deck winch was operated, the tension in the winch line was greatest at the first vertical run, and least at the last vertical run, because each time the line ran through a pulley it lost a small amount of force due to friction. When the deck pulleys were attached to the stay sheathing at the proper spacing, the highline could be made to lift and automatically align the sheathing at the angle needed for strand installation (see Figure 16). The highline then held the sheathing in place until a sufficient number of strands were installed to support the sheathing's weight.

Fig. 16 The highline system lifts the sheathing into place for Stay 18.

STRAND-BY-STRAND STAY INSTALLATION

All strands for the stays were installed and stressed one at a time using a system of pulling winches located at both ends of the stay cable. Two simple but very important pieces of equipment were used to facilitate the process. First, the seven-wire strands were connected to the pulling winch wires with a device called a kingwire coupler. Each strand end had its middle, or king, wire exposed by cutting away a few inches of the surrounding six wires. The kingwire coupler could attach and detach as necessary in a few seconds using a special set of pliers (see Figure 17). The kingwire coupler's outside diameter was slightly less than that of the strand itself, allowing the coupler to pass through the anchorages and stay cradle sleeves with ease. The second critical piece of equipment was referred to as a shuttle. This item allowed the pulling winch wire to connect to both the strand being installed and the return winch wire (for pulling the next strand back the opposite direction). Two shuttles were used for strand installation: one in the back span section of the stay and another at the cantilever section (see Figure 18).

Strands were installed by winching from alternating directions to maximize the efficiency of the operation. Two strands could be installed in one full winch cycle. First, a new strand was connected to the shuttle located near deck level at the back span end of the stay. This shuttle was then winched forward, carrying the strand and the return winch wire with it. After disconnecting from the back span shuttle, the strand and return wire were pulled through the cradle and reconnected to another shuttle near the cantilever side of the stay cradle. This second shuttle would then be used to pull the strand and return wire down to the cantilever anchorage. At this point, the back span shuttle was located at the stay cradle, and the cantilever shuttle was ready to connect to a second strand at deck level near the cantilever tip. The winching process was then reversed and the return winch wire was used to pull the second strand and the original pulling winch wire back towards the back span end of the stay. By alternating strand installation ends in this way, the shuttles never traveled the length of the stay without carrying a new strand.

Fig. 17 Kingwire coupler and disconnection tool.

Fig. 18 Shuttle used during stay strand installation.

MONOSTRAND STAY STRESSING

Freyssinet used their monostrand jacking system, called Isotensioning, to stress the strands in each stay. Stressing a stay cable in this manner requires the construction engineer to calculate an initial strand force that is higher than the final desired target force. As each new strand is stressed, the strands already present in the system shorten slightly and lose a small amount of force. Over the course of the installation of many strands, the force per strand drops significantly. The initial force selection for stressing this first strand is a function of several parameters including: the required "target" force, the actual length of the stay at the beginning of installation (which must be surveyed to be determined), the expected movement of the stay work points during cable stressing, and the nominal cable weight. In addition, the relative temperature of the stay strands and the bridge deck and pylon can influence the stay force.

For proper long term fatigue performance of the stay cables, the individual strands' forces must be as close to identical as possible. To achieve this, the Isotensioning system relied on two electronic load cells at each stay anchorage. One load cell was attached to the first strand stressed, which was designated as the "master" strand (see Figure 19). The second load cell was a part of the internal components of the monostrand jack, shown in Figure 20. Each time a new strand was stressed, it was tensioned until its force (from the jack's load cell) matched the force as read from the master strand's load cell. To maximize the accuracy of this matching, control of the stressing jack was taken over by a computer just prior its final stroke.

Fig. 19 Master strand load cell.

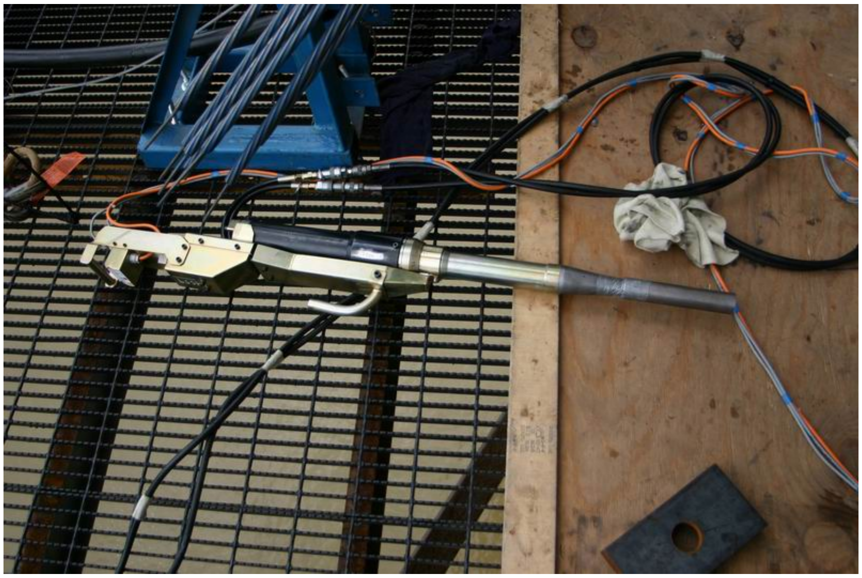

Fig. 20 Monostrand jack.

Each stay was stressed in two phases. The first stage, which included installation and stressing of the strands, brought the stay force to approximately 80% of its final target force. Because the strand installation process was much slower than the stressing process, this stage could last for several work shifts. During that time construction loads on the bridge could change and the structure could undergo several daily thermal cycles. These influences could potentially cause errors in the actual forces in each strand. Also, the deflection of the bridge at the end of Stage 1 was compared with the expected values to ensure that the structure was behaving as expected. If necessary, the Stage 2 master strand force could be adjusted to account for unanticipated behaviors. Stage 2 stay stressing lasted for only a few hours, minimizing the chances of unexpected load changes on the bridge and the effects of thermal changes in the structure.

For the Veterans' Glass City Skyway, each strand was stressed simultaneously at both anchors so that the precise force could be achieved without overcoming the coefficient of friction in the cradle sleeve and causing the strand to slip. Due to the asymmetrical method of cantilever construction, the stay forces on the cantilever side of the pylon were slightly higher than those on the back span side.

MAIN PYLON AESTHETIC FEATURES

A series of public meetings was held during the early stages of the design of the project. The purpose of these gatherings was to establish an aesthetic theme for the project and choose from a variety of options that would give members of the community a sense of ownership in the new bridge. Several aesthetic choices were made, including establishing the shapes of the approach piers and pier caps, selecting pylon shapes, choosing the type of traffic barriers, and deciding whether or not the bridge should be painted or left the natural color of concrete.

PYLON GLASS

Most importantly, the Task Force selected an overarching aesthetic theme of "Glass" to guide the decision making process and determine what special aesthetic features would be incorporated into the bridge. Although diminished somewhat in the past few decades, Toledo has historically had a strong presence in the glass-making industry, and is still known as "the Glass City." It was decided that glass would be a significant part of the aesthetics of the main pylon.

The development of the stay cradle and the resultant elimination of stay anchors in the pylon allowed FIGG much greater freedom to incorporate glass into the design. The final configuration chosen by the Task Force included glass panels on four sides of the upper 60 m (196 ft) of the pylon as well as a glass-clad, pyramid-shaped pylon top. Behind the glass were access shafts through which interior maintenance lifts could operate for maintenance and cleaning.

The glass panels were custom-designed to reflect the sky during the day but allow backlighting to shine through at night. The glass panels were heat-strengthened, laminated, and consisted of four separate layers. The outermost layer was a 9.5 mm (0.375 in.) thick layer of low iron content clear glass. Behind this layer was a 6.4 mm (0.25 in.) thick layer of clear glass with one third of the surface area mirrored in a pattern of vertical stripes. The third layer was another 9.5 mm (0.375 in.) clear glass panel, behind which was a 3.2 mm (0.125 in.) layer of glass with a patterned surface to diffuse light passing through it. The total thickness of the glass panel was 33 mm (1.3 in.) including the adhesive interlayers.

Each glass panel, as shown in Figure 21, was approximately 2.3 m (7.5 ft) wide and 1.4 m (4.5 ft) tall and weighed approximately 2.0 kN (450 lbs). Forty-four glass panels were attached to each quadrant of the pylon using an aluminum framing system made waterproof with structural silicone caulking, similar to systems found in high rise buildings. The system was designed so that individual glass panels could be removed and replaced without disturbing surrounding panels. During the design phase, the glass underwent a series of ballistics tests to ensure that the system would perform safely and all pieces of glass broken by the impact of bullets or debris would remain in place until the panel could be replaced.

Installation of the glass panels progressed quickly once the aluminum framing was in place. All 176 glass panels were installed in the pylon in approximately 10 working days over the course of two months. The final pieces of glass, located in the pylon peak, were installed the day before the bridge's Grand Opening ceremonies on June 23, 2007.

LED AESTHETIC LIGHTING

Perhaps the most spectacular and versatile aesthetic feature of the new Veterans' Glass City Skyway becomes visible at night. A total of 384 LED lighting fixtures were located behind the glass panels of the upper pylon and pylon peak. These fixtures are completely programmable using a personal computer and can be customized to display color schemes of the community's choosing.

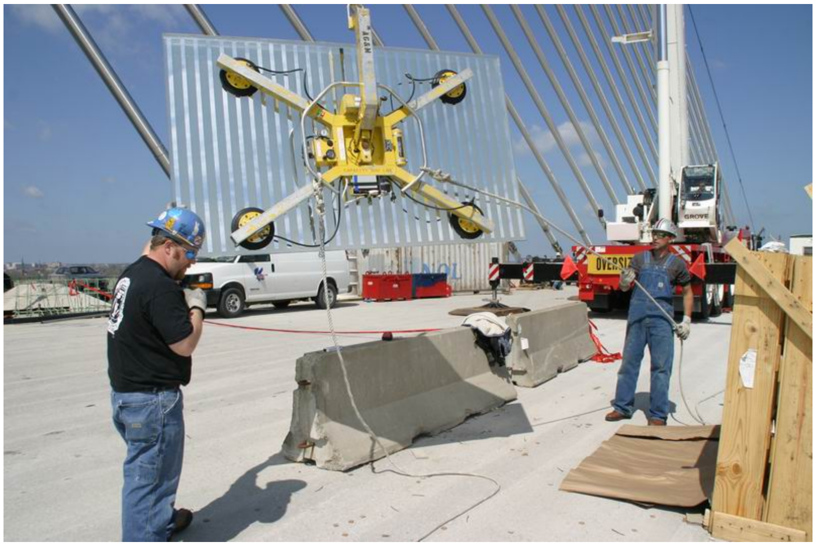

Fig. 21 A partially mirrored glass panel is prepared for installation into the upper pylon.

The Colorblast 12 Powercore fixtures were supplied by Colorkinetics. Each fixture contained a group of red, green, and blue light emitting diodes. By varying the intensity of each of these colors and mixing their light together by reflecting off of the curved and painted concrete surface behind the glass, each LED fixture could produce any of 16.7 million separate colors (see Figure 22). The fixtures could be combined to display either static or dynamic "shows" that represent various holidays, seasons, and special events throughout the year. The entire system was connected to an astronomical time clock to run from dusk to dawn every night of the year.

Fig. 22 LED light fixtures reflect red and green light off of the curved pylon concrete.

The highly power-efficient LED fixtures were completely watertight for use in outdoor applications, and were expected to last approximately 20 years before they would need to be replaced.

CONCLUSIONS

The new Veterans’ Glass City Skyway in Toledo, Ohio incorporates many unique structural and aesthetic features. It was constructed completely from the “top-down” by cantilevering in one direction from the main pylon over the main shipping channel of the Maumee River. All precast segments were delivered over the completed back spans, allowing uninterrupted shipping to the busy Port of Toledo.

The stays are the largest of any known cable-stayed bridge in the world, with up to 156 ~ 15 mm (0.6 in.) diameter strands. The bridge is the first in the United States to use low maintenance stainless steel stay sheathing, and the first to be designed with the new cradle system for passing the stay cables through the pylon.

The stay cradle provides an efficient means of transferring cable forces to the pylon concrete, eliminating the need for anchorages in the pylon and the associated additional rebar, post-tensioning, or steel anchorage box. The highly efficient force transfer also allowed the cross-sectional shape of the pylon to incorporate, for the first time in any cable-stayed bridge in the world, glass panels and multicolored LED lighting for the upper 60 m (196 ft) of the pylon above deck level.

The glass panels and LED aesthetic lighting represent less than 1% of the total project cost and are expected to require only minimal maintenance during the bridge's service life. However, the aesthetic impact of these first-of-a-kind features is extremely high, and the bridge is expected to become a new landmark not only for Toledo but for the United States (see Figure 23).

Fig. 23 The pylon is lit with a patriotic color scheme during the Grand Opening ceremonies.