Statement in Steel

By Kevin G. Wood, P.E.

A spectacular addition to the Milwaukee Art Museum is located on the shore of Lake Michigan in downtown Milwaukee. Set to open in the spring of 2001, the project represents the first completed building project in the United States for world-renowned architect Dr. Santiago Calatrava. One of the prominent features is metropolitan Milwaukee's second cable stayed pedestrian bridge (the first, spanning over U.S. Highway 41/45 in Menomonee Falls, was built in 1971.)

The addition to the museum provides approximately 125,000 sq. ft. of galleries, theaters, parking and other support services. The new cable stayed pedestrian bridge spans 232′ over busy Lincoln Memorial Drive and will provide a safe link for pedestrians walking from Milwaukee's downtown to the Art Museum's new entrance. Visitors can enter the museum's second floor directly from the bridge's back span, or they may descend a flight of stairs along the bridge's piers to enter on the ground floor.

The bridge contains several unique features. The backstay cables unconventionally fan out in three dimensions, creating curved geometric shapes. A single, angled pylon located at the east end provides the primary support for the main span by way of the cables. This pylon is supported by a dramatic combination of welded plate elements called the "hammerhead" and "boomerangs". The bridge's main span has an unusual five-sided closed shape, and is only two feet deep with 1′11″ high parapets.

The Milwaukee Art Museum had been outgrowing its original space, as well as an addition constructed in 1975, for several years. The Museum hired Dr. Santiago Calatrava as lead architect for the addition project. His design approach emphasizes the movement of forces that animate his structures. Dr. Calatrava's goal for the project was to provide additional display space, while at the same time creating a structure that would be considered a work of art in and of itself. Kahler Slater Architects of Milwaukee was hired as the Architect of Record.

Kahler Slater hired Graef, Anhalt, Schloemer & Associates of

Erecting one of the 48-foot-long main span girder field sections.

Milwaukee to provide structural, civil engineering services, as well as landscape architecture for the Art Museum Addition project. C.G. Schmidt Construction Management of Milwaukee was retained by the Milwaukee Art Museum as the Construction Manager.

Dr. Calatrava established the design concept, overall dimensions and material used to build the bridge. Several alternate cross sectional shapes and ideas were developed (round, triangular, glass deck, etc.) and compared before achieving a final solution. The final design provides a wonderful balance of strength and aesthetics. As the structural engineer of record, Graef, Anhalt, Schloemer & Associates assumed responsibility for determination of design loads and final design for the superstructure and substructure elements. GT STRUDL's frame, finite element and nonlinear routines were used for the structural analysis.

The superstructure and above ground portions of the substructure are made of ASTM A572 structural steel plates welded into closed shape sections. Many of these plates have been bent and rolled to create the unique cross sections of the members. Nine cable stays running down the centerline of the bridge provide primary support for the main span. Eighteen backstay cables hold back the pylon and are anchored to a tieback beam integrated into the building's roof.

Design

The cables are the primary means of support for the main span and provide restraint/stabilization for the pylon. Eight of the main stay cables are 50mm in diameter. All of the back stay cables, as well as the longest main stay cable, are 35mm in diameter. The longest main stay cable is smaller than the remainder for two reasons. First, since it is anchored very close to the west abutment, it carries less load and does not need the extra cross sectional area. Second, a 50mm diameter cable would have been heavier, carried less stress and resulted in visually unacceptable sag. Lengths range from 72 to 318′ for the 50mm cables, 68 to 101′ for the 35mm back stay cables and 352′ for the longest main stay cable.

Locked coil cables contain a core of conventional round wires surrounded by two or more layers of "z" shaped wires. The "z" shaped wires interlock tightly with each other when stressed, providing better resistance to water infiltration, a low void ratio and a smooth surface with a pleasing appearance. It is common practice to provide two lines of defense against cable corrosion for any cable-stayed bridge. For this bridge, each wire is galvanized. In addition, a flexible resin developed by the cable manufacturer fills the voids between the wires and coats the outside of the cables.

The Post-Tensioning Institute's Recommendations for Stay Cable Design, Testing and Installation was used to design the cable sizes. Maximum dead plus live load cable stresses were limited to 45% of the minimum cable breaking stress, which corresponds to an allowable stress of approximately 100 ksi. Permanent cable stresses above this allowable stress lead to steel relaxation and loss of cable forces. Since dead load stresses for the Art Museum bridge are kept well under the limit, relaxation is not a problem.

Three types of cable anchorages were used for this project. Fixed, open socket fittings anchor all cables to the pylon tabs. Adjustable block sockets secure the backstay cables to the tieback beam's tab anchorages and adjustable cylindrical sockets bear on the underside of the main span box girder.

The main span's support is provided along the bridge centerline by the main stay cables and at the west end by a simple steel frame abutment. Since this arrangement would allow an open section girder to teeter about these supports, forming the girder into a closed shape provides torsional rigidity. All plates of the cross section (with the exception of the deck plate) are 5/8″ thick, joined together with continuous welds. To control local deflections from pedestrian loading, the deck plate is 3/4″ thick. Slender plates are stiffened with longitudinal tee sections. As with all cable-stayed bridges, the girder is forced to bend about its weak axis under gravity loads for prevention of lateral/torsional buckling. For the Art Museum bridge, bending stiffness in the lateral direction is approximately 30 times greater than stiffness in the vertical direction.

The main stay cables pass through the girder body by means of an eight in. diameter extra strong pipe. Cable forces are delivered to the girder via the cylindrical socket's bearing nut. This bearing nut screws onto the cylindrical socket and bears on the end of the pipe. The pipe in turn welded to 1/2" thick vertical diaphragm plates that are then welded to the girder's deck plate and bottom flange. Internal transverse diaphragms provide stability for the vertical plate.

Using ASD methods, the main span box girder was designed as a beam/column. Pedestrian loading and self weight causes global bending. Compressive axial loads are introduced by the horizontal force component of each cable. These axial forces are zero at the west abutment/expansion end of the span and reach a maximum value near the pylon base.

Dr. Calatrava wanted the pylon to lean towards Lake Michigan at a 48-degree angle to match the spine of the building's dramatic Brise Soleil. Similar to when a fisherman leans back to land a large fish, the pylon pulls back on the cables to prevent the main span from falling to the ground. Since the pylon does not have enough self-weight to maintain equilibrium, backstay cables tie it down to the massive Art Museum superstructure.

The pylon cross-section forms a 198' long pipe of constantly varying outside diameters. These vary from 22" at the base, 39" at the 5th cable junction, down to 12" at the architectural tip. Plate thicknesses range from 1-5/8" between the base and 1st cable junction, 1-1/8" between the first and ninth cable junctions, and ½" above the last cable. Because the pylon experiences compressive axial loads from cable force components aligned with the pylon, and bending from variable cable forces and the wind, it was designed as a beam/column.

Three-dimensional through plate assemblies provide anchorage of the cables to the pylon. Anchorage plates were detailed so that the cable's lines of action crossed at the pylon centerline, thus eliminating any local eccentricities. The anchorage plates are 2-1/4" thick for the main span cables, and 1-1/4" thick for the back stays. Cable forces are directly delivered to the pylon by using full penetration groove welds to join the anchorage plates to the pylon shell.

Pylon forces are delivered to the substructure through a unique element called the "hammerhead". So named because of its appearance, the hammerhead is an elliptical shaped hollow beam 15' long. Pylon reactions are the point loads acting on the hammerhead. To obtain the greatest amount of strength and deflection control, the hammerhead's strong bending axis aligns perpendicular to the pylon axis. Four 1-5/8" thick plates rolled to form ellipses form the hammerhead shell. The ellipse is 3'-10 5/8" deep along its major axis at the pylon, tapering down to three ft., three in. at the piers. It is 2'-11 ½" wide at the pylon, and two ft., six in. wide at the piers. The elliptical shells are welded to a four in. thick continuous plate that forms the hammerhead's internal web. This web plate, which carries approximately two-thirds of the total bending, extends through the tops of the piers and into the building's concrete ring beam. Full penetration groove welds join the elliptical plates to the inside face of the piers.

The building's "ring beam" and the bridge's piers work together to resist the hammerhead reactions. The cast-in-place, post-tensioned concrete ring beam is a free-form portion of the new addition that also provides anchorage for the backstay cables. Fifty-four ring beam post-tensioning tendons pass through each end of the hammerhead's web plate. These tendons resist the horizontal component of forces in the hammerhead. The "boomerang" piers, another element so called because of its shape, resist vertical reaction components. The boomerangs must also resist the axial force and bending moment from the main span box girder, and act as stair stringers. Complicated loading, three dimensional shape, and constantly tapering cross sections of this member dictated that a finite element analysis be performed to properly model its behavior.

The boomerang section above the main span deck elevation is 13' long, and the section below is 27' long. Sections vary from three ft. to five ft. for depth, and one ft., two in. to 1'-10" for width. Each boomerang is built with 1-5/8" and

Pylon anchorage detail.

Pylon pick (note pallets of coiled cables in the foreground).

two in. thick plates that form a five-sided cross section. All plates are joined using full penetration groove welds. Since the bend of each boomerang behaves as a rigid frame knee, three in. thick plates are required to form the radius of the compression flange. One-inch thick internal stiffeners help to prevent this radiused plate from punching into the knee as the external forces try to “close” the boomerang.

Fabrication

Extensive ultrasonic testing and visual examination of the weldments were employed as part of the fabrication quality assurance effort.

Duwe began the project by building the main span box girder sections. The 24′ spacing of the main stay cables allowed them to utilize standard eight ft. plate widths to fabricate eight ft. long girder units. Because the camber of the bridge is circular, 18 of the 29 girder sections were identical. The remaining 11 sections include nine anchorage units and two end units. An unexpected benefit of the standard length was that the camber could be formed without tapering the units. Prequalified weld root tolerances allowed a vertical kink to be formed at each transverse welded connection, thus forming the desired bridge profile.

Templates formed the cross section of each eight ft. section. Each section was made from flat and bent plate, joined with partial penetration and continuous fillet welds. Full penetration groove welds were then used to create 24′ long shop units by combining two standard units with one anchorage unit.

To maintain the construction schedule, the boomerangs were fabricated next. Several steps created sections light enough for Duwe to safely handle and position in their shop, as well as sections small enough for ease of shipment to the job site. Each boomerang was laid out flat on the shop floor with loose plates to verify plate fit-up prior to welding. After welding, the lower leg sections of each boomerang were cut off, done so that the upper portions could be erected vertically in the shop for fit-up (but not welded) with the east end main span unit. Duwe welded temporary struts onto the upper boomerang legs, and cut the upper legs off from the “knuckle”. The next step was placing the four in. hammerhead web plate into slots formed at the boomerang upper leg tips. This assembly formed one shop unit. The lower boomerang leg sections were rewelded to their corresponding knuckle sections, and these pieces formed the second and third shop units.

Compared to the boomerangs, the hammerhead was a fairly straightforward component to fabricate. After placing and welding the web plate into the boomerang upper leg slots, the four tapering elliptical shell plates were joined to the web plate and each other with full penetration groove welds. Architectural steel castings form the smooth transition from the hammerhead to the pylon.

The toothpick shape of the pylon was created from several tapering sections of rolled plates. Taper transitions occur at each anchorage. Detailing the transitions to occur only at the anchorages minimized the number of transverse joints required to fabricate the pylon. This was also the only reasonable way the “whale tail” backstay anchorage plate could penetrate the pylon shell. Full penetration groove welds were again joined the pylon pipe sections, as well as to close the longitudinal seam of the rolled plate.

Only a handful of cable manufacturers produce locked coil cables. Bridon Structural Systems, Ltd., of Doncaster, United Kingdom, is one of them. Bridon required several pieces of information from the design team to properly fabricate the cables, including final cable tension under dead load and the corresponding cable sag length. Using this information, the cable manufacturer cuts each cable to length and attaches all anchorage hardware in Great Britain. Only minor adjustments are possible on site. Since the cylindrical sockets used at the main span anchorages allowed only 10″ of total adjustment, extremely accurate calculations of the individual cable lengths were required. Lengths were checked and rechecked at our office; both Performance Detailing and Bridon performed independent checks. A final piece of information Bridon required was where to locate the bearing nut on the cylindrical socket threads under dead load. To give the erection crew the maximum amount of play possible (five in. of tensioning or detensioning adjustment), a location was specified at the middle of the threads.

Hammerhead placement on the boomerang piers.

Erection

The first elements to arrive on site were the lower parts of the boomerangs. Each was positioned on their respective base plates and plumbed. Next, the east end main span unit was erected on shoring and welded to the boomerangs. With the lower boomerang sections tied together, the hammerhead/ upper boomerang leg assembly was welded to the lower boomerang sections, completing the pier.

The main span girder arrived on the job site in 24′ shop lengths. C.D. Smith welded two shop units together on the ground to make 48′ field units, then picked for final placement. Using this procedure cut in half the number of overhead field welds required.

Most cable stayed bridges span over water, and a cantilever method of erection is typically employed to avoid expensive underwater shoring. Because the Art Museum bridge spans over land with a maximum ground clearance of only 20′, it was much more cost effective and safe to place the main span sections on shoring. Erection proceeded from the boomerangs towards the west abutment. Each 48′ section was picked and placed on the shoring, and the sections were welded together. All transverse joints were ultrasonically tested. Upon completion, temporary concrete blocks on the deck simulated permanent dead loads not yet in place.

After completion of the main span, the back span was erected. The back span is a 50′ box girder supported by the main span at the west and eye bar hangers on the east. Interference with existing construction forced the steel erectors to fish the back span through the opening formed by the hammerhead, boomerangs and main span before setting it on shoring, which was then welded to the main span and connected to the eye bars.

The pylon arrived on site in three shop sections. Similar to the main span, the pylon sections were welded together on the ground. Pylon erection was the most dangerous part of this project. Two cranes were required to maintain the pylon's 48-degree angle. Once in position, backer bars at the top of the hammerhead doubled to keep the pylon base aligned. With the cranes providing support and control, the pylon's self weight slowly pushed itself home over the backer bars and onto the hammerhead.

In addition to supplying the cables, Bridon Construction Services Department did the cable erection and tensioning. Immediately after the pylon was seated, two main stay and four backstay cables were erected at the fourth and fifth cable junctions. The fixed cable ends were pinned to the pylon, and then the adjustable ends brought into position using come-alongs. These first six cables were slowly tensioned until the pylon load was removed from the cranes. The pylon was then welded to the hammerhead.

In accordance with our tensioning procedure, Bridon next erected the cables in groups of six, starting at the bottom of the pylon and working their way up. Each cable was tensioned in three stages. Cables were tensioned to approximately 33% of their final load in the first stage, 66% in the second and 100% in the third. The temporary concrete dead loads on the deck ensured proper loads would remain in the cables after all permanent dead loads were placed in the future. Cables were tensioned using jacks, and the force in each was established by correlation of the jack's fluid pressure and piston area. Bridge behavior during cable tensioning followed the computer model closely, lifting off of the shores during the second and third tensioning stages.

The success of this project was the direct result of spirited cooperation exercised by all parties involved working as a team. This project was extremely challenging, and it was understood from the beginning that communication and patience would be the keys for completing the work correctly and safely. All members of the project team worked closely with each other throughout all phases of design, fabrication and construction. The result of this teamwork speaks for itself.

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