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SYNTHESIZING FORM AND FUNCTION

The Damen Avenue Arch Bridge was not simply an innovative engineering feat, but also a success as a new neighborhood landmark

By Patrick Cassity, P.E., S.E., Martin Furrer, P.E., and Ken Price, P.E.

IT IS BECOMING INCREASINGLY VITAL THAT MODERN BRIDGE STRUCTURES be optimized for aesthetics and speed of construction, as well as for function and efficiency. This is particularly true of highly visible bridges in urban areas that are heavily relied upon for commerce, safety and mobility.

Aesthetics are playing a more significant role in the selection of bridge types and details. Owners and the general public recognize that beautiful bridges add value to the community. This value can come in both tangible and intangible forms. Beautiful bridges can stimulate development and revitalization of the surrounding area, increase revenue from tourism and promote the general well-being of the community itself. Furthermore, landmark bridges can become an identifier or signature for the community as a whole.

Disruption of traffic during construction can result in significant costs to motorists and surrounding businesses. Traffic disruption costs are considerable for toll highways, interstate routes and in metropolitan areas. User costs from lost productivity and vehicle operation can add up to hundreds of thousands of dollars per week depending upon the magnitude of traffic delays during construction and the traffic volumes.

It is precisely for these reasons that municipalities such as the City of Chicago strive to minimize construction duration and ensure that the end result is a beautiful bridge that appropriately compliments the surrounding community. One notable example of such a project is the new Damen Avenue arch over the North Branch of the Chicago River.

When the City of Chicago asked J. Muller International to design a signature bridge at this site that could be opened to traffic within eight months, we sharpened our pencils and began the task of balancing functionality, constructability and aesthetics to conceive a structure that best met the project goals.

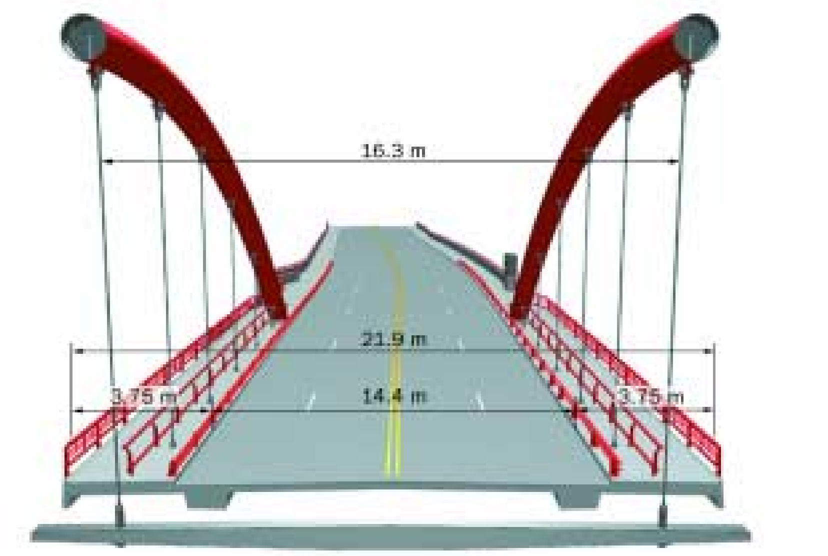

Figure 1

PROJECT OVERVIEW

The bridge is part of a $12.6 million improvement project along a section of North Damen Avenue that is located 6 kilometers northwest of downtown Chicago. Improvements to the approach roadway consist of smoothing out a substandard alignment adjacent to the bridge, demolition of a viaduct structure that is functionally obsolete and street-scaping of the roadway corridor.

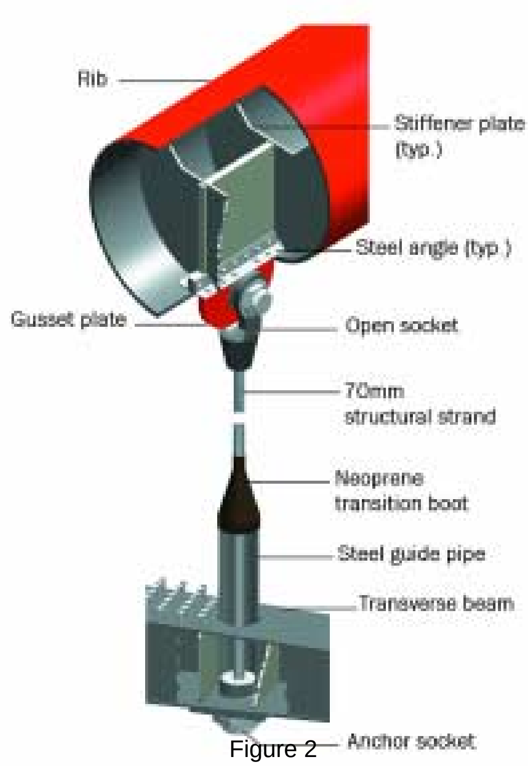

Figure 2

The mixed-use properties surrounding the site are rapidly transitioning from factories to mini-malls and condominiums. The City of Chicago also has future plans to construct a riverfront walkway and bicycle path that will extend along the river and under the new bridge. A wetland area, nature trail and boat launch will be built adjacent to the bridge site as part of the riverfront improvements. The bridge has become a catalyst for the overall public and private revitalization of the area.

The new structure spans 94 meters over the river, carries two lanes of traffic in each direction and has sidewalks along

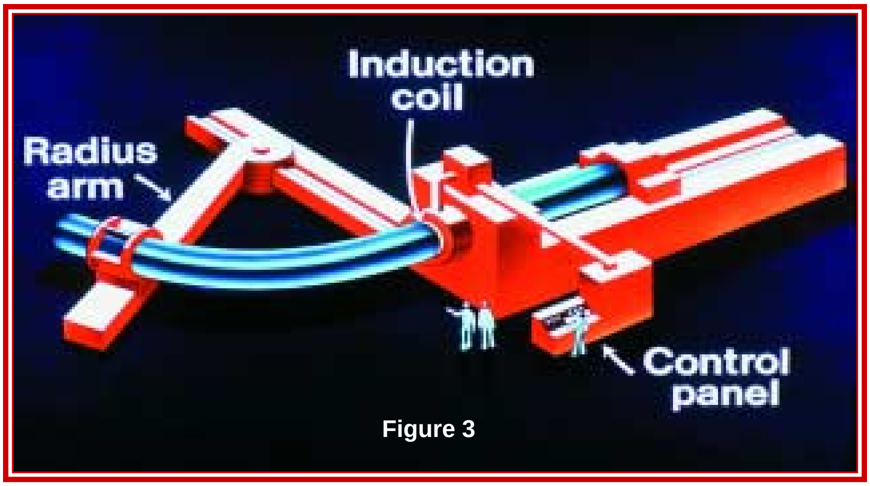

Figure 3

Figure 4

each side. The two ribs are fabricated from 1.2-meter diameter steel pipe that is formed into a compound circular curve using induction heat bending. Each rib lies in a vertical plane and is located between the roadway and sidewalks. The ribs have a constant wall thickness of 25 millimeters throughout their length. Each rib is filled with concrete over a distance of eight meters at each end to resist the higher thrust and moment near the spring points.

The superstructure is comprised of a longitudinally post-tensioned, cast-in-place concrete deck and stiffening girders that are supported by transverse steel box beams (see Figure 1). The transverse beams act compositely with the deck. The beams are supported from the ribs by structural strand hangers that are anchored at the bottom flange and attached to the ribs using steel gusset plates and an open socket. The gusset plates penetrate the rib and are welded to stiffener plates and bolted to angles to transfer the hanger forces into the rib (see Figure 2).

The semi-integral abutments and rib thrust blocks are founded on a common reinforced concrete cap. Each cap is supported by six 2.1-meter diameter drilled shafts that extend to bedrock.

Design Innovations

The structure utilizes three major innovations to advance the state of the art in steel arch bridges and satisfy the project goals: the ribs are free-standing and constructed without lateral bracing; the ribs are fabricated from large diameter structural steel pipe; the arch is untied.

Two of the innovations are interrelated in that the use of an aerodynamically efficient rib shape significantly reduced wind pressures on the rib to allow for the elimination of bracing. The use of an inherently stable pipe section also eliminates the need for longitudinal stiffeners and diaphragms to provide local stability to the section.

The elimination of lateral bracing between the ribs was one of the primary aesthetic goals identified during concept development. Because of the relatively large distance between ribs compared with the short rise of the rib above the roadway, lateral bracing makes the overall structure appear boxy and constricting. The elimination of bracing results in cleaner lines that bring to light the naturally elegant form of the arch and create a more open space for the motorists and pedestrians using the structure.

The FHWA and the Illinois Department of Transportation preferred that a tension tie not be employed to resist the lateral component of the arch thrust. Their primary reason was due to concern regarding the lack of structural redundancy in the event of a tie failure. Therefore, the final structural scheme mobilizes frame action in the foundation and the elastic lateral support of the surrounding soil to resist the lateral component of the thrust.

Global Stability

Due to the fact that lateral bracing has been eliminated between the arch ribs, the buckling capacity of the ribs was carefully assessed to ensure stability of the structure and determine the allowable design compressive strength of the ribs. Second order elastic buckling analyses were carried out for load cases involving dead, live and wind loading to determine the critical axial buckling load.

Initial out-of-plane imperfections were of concern since parametric studies have shown that out-of-plane deviations in arch geometry can reduce the ultimate strength of steel arches that are governed by lateral instability. Therefore, initial out-of-straightness of the rib was considered to assess the sensitivity of the ribs to geometric imperfections introduced during fabrication and erection. Buckling analyses were performed assuming an out-of-straightness criteria of Rise/750 (25 millimeters).

The moment of inertia corresponding to out-of-plane bending was reduced to account for a potential ovalization of three percent in the cross section during bending of the pipe. This number is consistent with the maximum allowable tolerances for induction bending of a pipe with geometric characteristics and radii consistent with the ribs.

Buckling analyses were performed for the rib alone, with the hanger forces applied as concentrated loads, and for the entire structure to examine the overall increase in the buckling capacity of the rib due to the stiffness provided by the hangers and deck. The buckling analyses results are shown below in Table 1.

As seen in Table 1, the hangers fail prior to developing any in-plane or out-of-plane elastic instability in the rib. Therefore, the critical buckling load used to determine the allowable design compressive strength was limited to the point at which the hangers fail. Examination of the results also indicates that the stiffness or support provided by the deck and hangers can theoretically increase the elastic buckling capacity of the rib by a factor of approximately 2.5 if the capacity of the hangers and connections is increased.

Buckling analyses were also run for a perfectly plumb rib to determine the sensitivity of the buckling capacity to initial imperfections in the rib geometry. The results indicated that load cases involving out-of-plane loadings were unaffected by initial imperfections, but the DL + LL elastic buckling capacity was reduced by approximately 30 percent.


Figure 5


Figure 6

Wind Analysis

The AASHTO design wind pressure of 3.6 kPa (2.4 kPa windward rib, 1.2 kPa leeward rib) for typical arch structures was determined to be too conservative when applied to this specific structure. The AASHTO recommended pressures were developed based upon an assumed wind speed of 45 meters/second and parallel, rectangular ribs connected by lateral bracing. Wind loads for this structure were determined in accordance with ASCE/ANSI 7-95 for the specific site, geometric characteristics, and dynamic characteristics of the bridge.

The 100 year basic wind speed for this site is 43 meters/second. The basic wind speed was varied over the height of the ribs according to the power law constant for suburban terrain. The wind engineering consultants, RWDI, recommended using a gust effect factor of 1.24 when calculating pressures applied to the rib. A drag force coefficient of 1.03 was also recommended. This factor accounts for the wind turbulence-structure interaction as well as the dynamic amplification effect caused by gusts in resonance with along-wind vibrations in flexible structures. The force coefficient of circular sections generally ranges from 0.5 to 1.2 while rectangular sections range from 1.3 to 2.0. Therefore, a significant reduction in wind pressures can be realized when using more aerodynamic shapes such as pipes.

The calculated design pres-

Table 1. Buckling Analyses Results			
Load Case	Factor of Safety		
	Elastic Buckling Rib Alone	Hanger Failure Entire Structure	Elastic Buckling Entire Structure
DL + LL	2.7	4.1	6.7
DL + W	2.9	4.5	6.7
DL + LL + 0.3W	2.7	4.1	6.5

Figure 7

sure varied from 0.83 kPa at the base of the ribs to 1.3 kPa at the crown. This represents an overall wind load on the windward rib that is less than one-half of the AASHTO recommended wind loading. The AASHTO recommendation likely assumes a force coefficient that is two times greater than the force coefficient for this particular structure.

Load combinations including wind did not govern the strength design of the rib; however, excessive deformation due to wind loading represented a serviceability concern. Deflection of the ribs was checked using a 20 year wind speed with a limiting deflection criteria of Rise/300 (62 millimeters). The computed maximum wind deflection is 50 millimeters.

Live Load Deflection

The overall bridge is extremely stiff when subject to vertical loading. The backspans help to stiffen the cable-supported main span. The longitudinal concrete stiffening girders and deck are very effective in distributing live load to the adjacent hangers. The live load deflection criteria used for design is based on the FHWA publication on the design of arch bridges with the allowable deflection reduced to account for the presence of pedestrians. The maximum live load is 24 millimeters compared with an allowable deflection of 49 millimeters (Span/1500).

Fabrication & Construction

The contractor started work in April 1998. The bridge was opened to traffic in December 1998 and completed in May 1999.

Rib procurement and fabrication were recognized as the most critical items affecting the overall construction schedule. Therefore, the contractor was presented with the following material options for the rib:

API 5L Grade X52 pipe
AASHTO M270 Grade 50 plate rolled and welded according to ASTM A381

These options were designed to give the contractor added flexibility to minimize the procurement period for the rib steel.

Each rib is comprised of 14 shop sections bent to a specific radius using induction heat bending. Induction bending utilizes an induction-heating coil to create a narrow, circumferential, heated band around the material to be bent (see Figure 3). Typical carbon steel material is heated to a temperature of 1000°C. Once the heated band has attained the desired temperature, the material is moved through the coil at a predetermined speed. A radial arm that rotates about a central pivot point and is clamped to the leading edge of the pipe applies the bending moment. After the material passes through the coil it is quenched by an air or water spray. The fabricator was able to increase the yield strength of the steel by about 30 percent as a secondary benefit of the heat treatment.

The contractor elected to fabricate each rib into two field sections weighing 53 and 21 tonnes each. The larger sections were barged from the fabricator's shop in Duluth, Minnesota through Lake Superior, Lake Michigan and up the Chicago River to the site. The smaller sections were trucked to the site. The sections were erected from the riverbank with a Manitowoc 4100W ringer crane that had a 73-meter boom.

The larger sections are 62-meter long and were picked directly from the barge and set into their final position (see Figure 4). The lifting beams were equipped with a series of shackles to allow the rib to rotate into its final upright position as it was lifted. Because the crane was located on the opposite side of the river, the 21 tonne sections required a pick radius of 70 meters. The short sections were temporarily supported by structural scaffolding near the field splice.

The overall configuration of the structure was selected to minimize the amount of falsework required to construct the superstructure. The superstructure was erected without any falsework located in the river (see Figure 5). Only two temporary falsework bents were necessary at the midpoint of each backspan to support the transverse steel beams at those locations until the concrete was cured and post-tensioned. The ribs, hangers and transverse beams supported the remaining formwork for the casting of the deck and stiffening girders.

The roadway deck and stiffening girders were cast in one continuous operation (see Figure 6). A total of 615 cubic meters of concrete was placed over a period of 7 hours. The concrete was placed using two separate crews, concrete pumps and screed machines that started at the midpoint of the bridge and worked outward to each abutment. Each crew was restricted to advancing no more than one bay out-of-balance from the centerline of the arch with respect to the opposite crew. A symmetrical concrete placement sequence was necessary in order to prevent overstressing of the ribs.

Rib erection, hanger and beam erection, superstructure casting and post-tensioning, approach slab placement and traffic control installations were completed in approximately 1½ months. This is a remarkable construction scheduling and engineering achievement by the contractor that, in our opinion, was facilitated by the configuration and details of the structure.

CONCLUSIONS

Government agencies, special interest groups and the general public are becoming less tolerant of the impact that highway construction has on traffic and the surrounding community. These same groups insist that highly visible bridges be designed to make a statement while achieving harmony with the surrounding area. It is no longer acceptable to view bridges as purely utilitarian structures and select bridge types based solely upon the criteria of least initial cost.

At the same time, initial costs cannot be significantly higher than a more conventional bridge due to the availability and demand for funding. The Damen Avenue arch demonstrates that landmark bridges can be cost effective and contained within the limitations of existing budgets.

A well detailed and designed structure is essential for success. The Damen Avenue arch was completed with less than ½ percent of the actual cost claimed by the contractor as an extra.

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