Engineering innovation in arch design

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ABSTRACT: Most modern arches are either true arches or tied arches. The modified tied arch in Michigan USA combined the two concepts for aesthetic and safety reasons. Tied arches, where the tie is exposed, might be hit by trucks and are not desirable for grade separation structures. True arches where the thrust must be taken by the foundation elements are exposed to risk when the soil conditions are poor. The Michigan arch is modified to look like a true arch with a tied foundation. The thrust blocks are connected below the roadway by a rectangular concrete tie beam. The arch ribs are unequal to keep the two bridges closer together. The stiffness of the ribs is varied to keep the same deflection. To allow for inspections without disturbing the heavy traffic, the ribs were sealed and pressurized and pressure gauges were added to detect any leaks.

1 INTRODUCTION

Modern bridges are either tied arch or true arch. Tied arches are efficient and particularly economical for single span arches. The foundations are much simpler and carry only vertical loads. They are ideal for river crossings. However, bridges over road traffic are vulnerable to being hit by traffic. True arches are generally aesthetically pleasing and desirable for grade separation structures. The cost of true arches, in general, is relatively higher than a tied arch. The I-94 bridge over Telegraph Road in Michigan, USA is a combination of the two. Although designed for six lanes of traffic, each bridge currently has three lanes open, with the option of opening a fourth lane in the future. The Michigan Department of Transportation predicts that 130,000 vehicles per day will traverse the eastbound and westbound lanes.

Figure 1 : Arch Bridge Maintains Sight Distance

2 PROJECT OVERVIEW

The bridges carry interstate traffic over a newly reconstructed I-94 Interchange at Telegraph Road. The Single Point Urban Interchange (SPUI) minimizes the needed Right-of-Way (ROW), but the SPUI requires single-span bridges to ensure adequate sight distance for traffic.

A typical conventional single-span structure (i.e. plate girder, bulb tee, etc.), requires a minimum construction depth of 8’, which reduces the minimum underclearance required under the bridge. One of the project requirements is to maintain the 14’-9” existing clearance under the bridge. With a conventional bridge the I-94 profile would need to be raised or the Telegraph Road profile lowered, in order to maintain the required clearance.

An arch bridge would avoid this raise, maintain clear sight distance by eliminating the center pier, improve aesthetics at the interchange and minimize changes to the physical environment. The superstructure depth of the arch bridge is 5’, which fits the existing vertical clearance under the bridge.

3 INNOVATION THROUGH VALUE ENGINEERING

The project team was challenged with two major criteria: cost and structural integrity. The team approached the design by analyzing its functions and its worth. The team value engineered the conventional design of elements and identified the function, cost and performance of each element. If the function need/performance is high and cost is low, it has value. If the function need/performance is low and the cost is high, it becomes a mismatch. See Fig.2. When mismatches of conventional design are identified, the team develops innovative solutions to create value of the elements that has a higher need/performance at a lower cost.

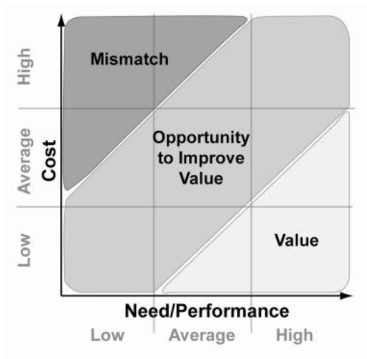

Figure 2 : Value Mismatch graph

The primary feature is the introduction of the foundation system with buried ties. A tied arch over a heavily travelled roadway is vulnerable to being hit. Its performance is low and it is a mismatch. A true arch is aesthetically appealing. However, soil conditions were found to be very poor. This raised concerns about the long-term foundation stability due to soil creep. With a high cost of a true arch and low foundation performance, it also proved to be a mismatch. With the two conventional designs that have mismatches, the team developed the concept of a longitudinal tie under the roadway. The design included multiple redundancies as explained in section 4.7 of this paper. The cost of the foundation was dramatically reduced by reducing deep foundations required to resist arch thrust. The concerns of poor soil and protection of the tie were resolved. The solution had the highest value. See Fig.3.

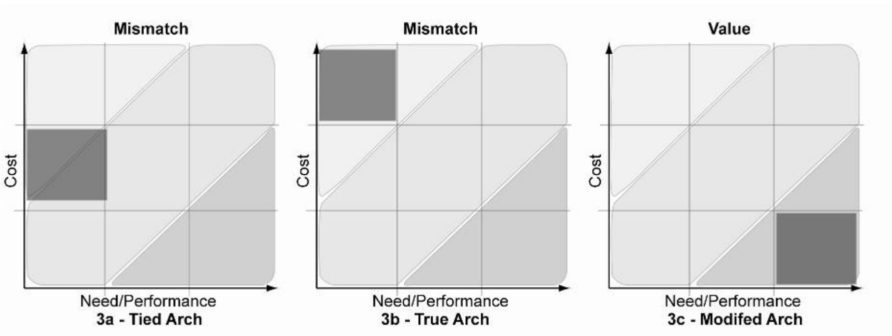

Figure 3 : Arch Types

The second feature is the pressurization of the arch ribs. The rib section is too small to inspect inside. Future manual inspection and maintenance cost would be high since part of the roadway would be closed during inspection or maintenance. The pressurization, as explained in section 4.5, will reduce the maintenance and enhance the inspection. It is categorized as a value to the project. See Fig.4.

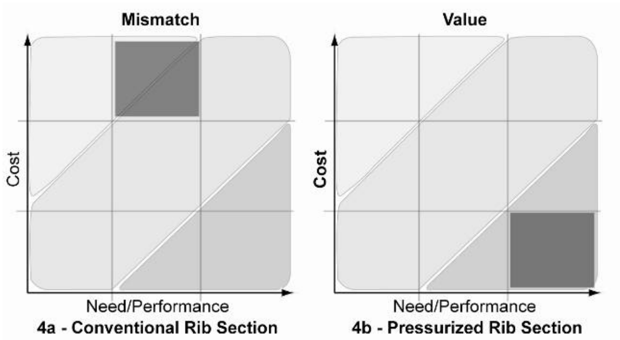

Figure 4 : Maintenance of ribs

The third feature is the optimization of the floor system. The floor system was analyzed for eight stringers versus four stringers. The performance of an additional four stringers did not decrease the deflections drastically while the cost was doubled. In addition, the moment connection was found to be expensive and was a non-factor compared to a simple connection. Section 4.2 presents these findings. The four stringer system with simple connection and two outer stiffening girders performs well at a lower cost and is a good value. See Fig.5.

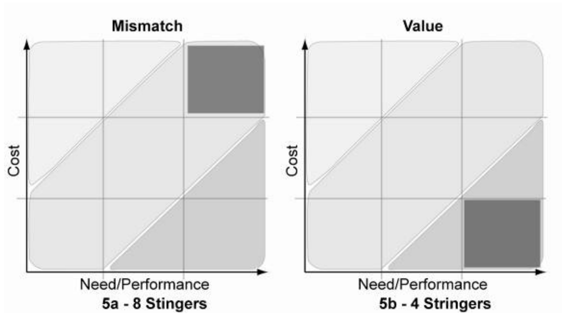

Figure 5 : Optimization of floor systems

The fourth feature is the introduction of a redundant second strand at each hanger assembly. This increased the redundancy of the hanger assembly and the bridge. Each strand is capable of carrying the load. In the future each strand can be replaced without temporary shoring since the second strand will carry the load during replacement. Additional cost of \$180,000 is about 1% of the total cost. For a small cost increase the performance is increased, thus producing value. See Fig.6.

The fifth feature is the combination of box and plate girder sections for the transverse beams. I-beams compared to box beams are economical and easy to inspect. At the end, due to the multiple strands, the beams may be subjected to torsion during strand replacement. The performance of the plate girder at the end will be low, since it is weak when subjected to torsion. The transverse beam is designed as a plate girder section in the middle and converted to a box section at the ends. This maximized its needed performance in the middle and at the ends within a reasonable cost. See Fig.7.

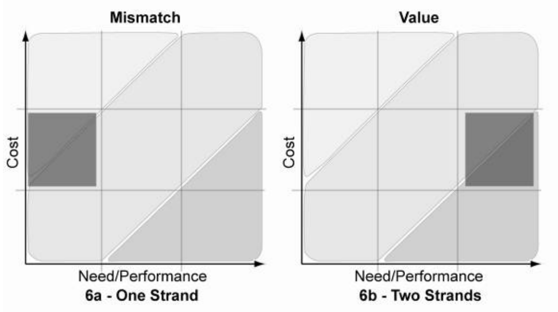

Figure 6 : Redundancy of hanger assembly

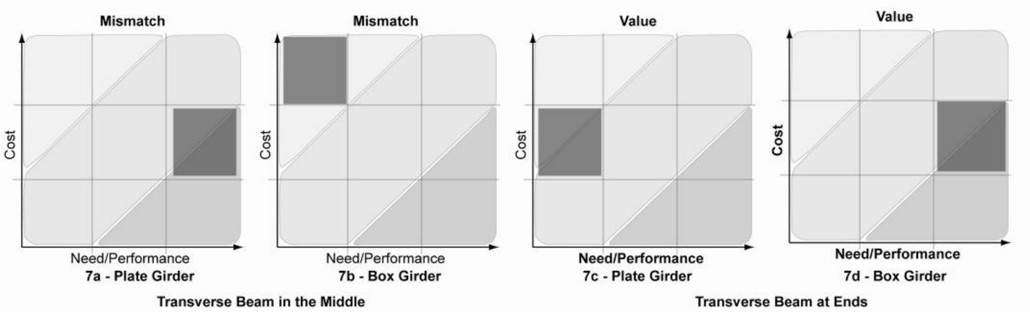

Figure 7 : Transverse beams

4 PROJECT ELEMENTS

4.1 Arch Ribs

Each structure is a single-span inclined through arch. The interior and exterior arch ribs are inclined 25 degrees towards each other. The inclination is limited to 25 degrees in order to maintain the desirable vertical clearance. The ribs are braced together using five football shape braces. The bases of the exterior arch ribs are located at Telegraph Road, while the bases of the interior arch ribs are located at the I-94 level. This caused the length of the exterior rib and the interior rib to be different. The length of the exterior and interior arch ribs is 296’ and 257’, respectively. The span length measured between the east and west abutments is 246’.

The unequal lengths of the arches posed a challenge to the design team. The arch rib deflection due to dead and live load will be different. By carefully varying the stiffness of the box while maintaining the outside shape and dimension the same, both the appearance and structural integrity were achieved. The inner thrust block is at the road level of the interstate: the outer thrust block is at the level of the local road. See Fig.8.

The ribs are fixed at each end by the foundation. The arch ribs are 3’ x 4’ box-section. The webs of the ribs are ¾” thick. The flanges for the exterior ribs and interior ribs are 2 ½” thick and 2 ¼” thick, respectively.

4.2 Floor system

The floor system is very economical. This is due to optimization of the number of stringers and the type of connections. The superstructure is comprised of a 9” thick, cast-in-place reinforced concrete deck, four W 18 x 65 stringers and two 38 1/2” deep stiffening girders, all supported by 14 transverse steel beams, which are equally spaced at 16’-5”. The transverse beams, stiffening girders, and stringers act compositely with the deck. Live load including impact (LL+I) deflections were checked for four-stringers and eight-stringer system with two outer stiffening girders. The difference is about 2% maximum (see Fig.9). Also, moment connections versus simple connection of stringers were analyzed for LL+I deflections. The difference is about 6% maximum (see Fig.10). Four stringers with simple connection and two stiffening girders with moment connection were adopted.

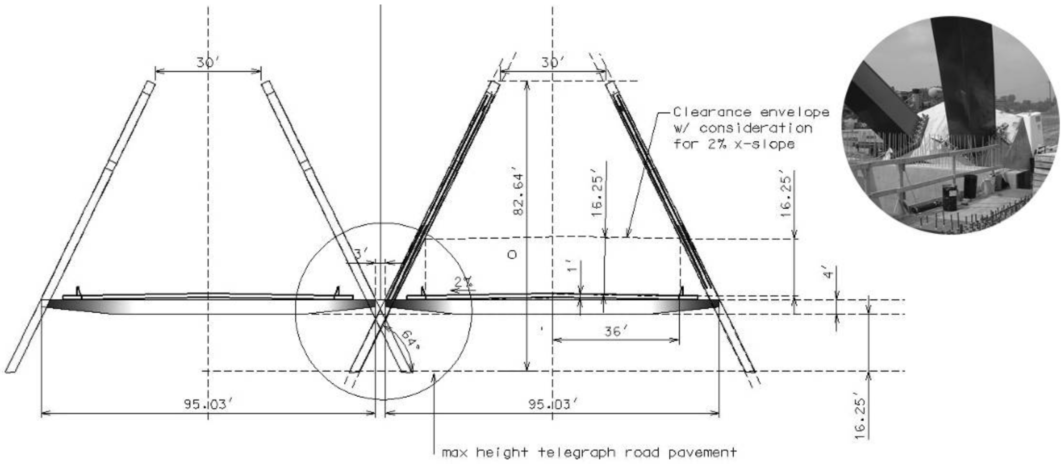

Figure 8 : Unequal Length of arches

4.3 *Transverse Beams*

LL+I Deflections due to 6 HS-25 Trucks			
Element	8 stringers + 2 Stiff. Girders	4 Stringers + 2 Stiff. Girders	Change
Exterior Arch Rib	1.84" (span/1926)	1.88" (span/1899)	+2.2%
Interior Arch Rib	1.45" (span/2127)	1.51" (span 2042)	+1.34%
Deck System	2.61"	2.63"	+0.8%

Figure 9 : Comparison of number of stringers

LL+I Deflections due to 6 HS-25 Trucks		
Moment Connection	Simple Connection	Change
1.78" (span/1926)	1.88" (span/1899)	+5.6%
1.45" (span/2127)	1.51" (span 2042)	+4.1%
2.48"	2.63"	+6%

Figure 10 : Connection for Stringers

The transverse beams are I-beams with a box end section for torsional stiffness and aesthetic reasons. The I-beams are economical and easier to inspect. The end portions are boxed using two additional outer webs. The boxed sections of the beams improve aesthetics and increase the torsional resistance of the beams in case one strand within the hanger assembly is lost or replaced.

4.4 *Hangers*

Each hanger assembly consists of two 2⅛" diameter, ASTM A586 structural strands, spaced 1'-3" center to center (see Fig.11). The inner wires of each strand are galvanized with Class A coating, while the outer wires are galvanized with Class C coating. Each strand is attached to the arch ribs using a 1-3/4" thick hanger support plate and ASTM A148 Grade 105/85 galvanized open type socket.

Neoprene transition boots (see Fig.12), secured to 10" diameter standard pipe, welded to the transverse beams and to the strands using stainless steel clamps, are used to prevent moisture from entering inside the connections between the transverse beams and the strands and to enhance aesthetics. A hanger separator is installed between the two strands of each hanger assembly for the middle ten hangers. Hanger separators increase the in-plane stiffness of the strands by constraining the relative motions between them and increasing the stiffness of the hanger against transverse winds.

Figure 11: Hanger assembly – two strands

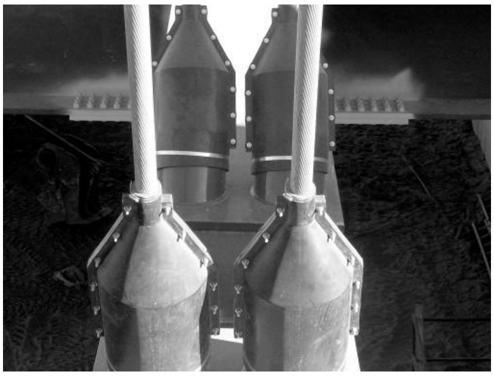

Figure 12: Neoprene transition boots

The bridge was designed to facilitate the replacement of individual strands. Each strand of the pair is capable of supporting the deck and the full live load while the other is replaced.

4.5 Pressurization

Due to the small size of the arch ribs, future inspection and maintenance of the inside portion of the box is virtually impossible. Therefore, the arch ribs, arch braces, and the boxed-sections of transverse beams are pressurized with dry air to prevent moist air from entering the boxed-sections to cause corrosion. In order to prevent any air leakage from the pressurized sections, the top flanges of the arch ribs and braces are welded to the webs using full penetration weld. The bottom flanges are welded to the webs using double side fillet weld. A trapezoidal shape-sealing diaphragm is located inside the arch box at each hanger location. The portion inside the sealing diaphragm is not pressurized, and an access opening in the web is provided to facilitate inspection of the unsealed portion of the arch.

Access openings in the arch ribs are furnished where the air pressure can be checked. At each arch rib field splice location, one pressure valve is attached to the sealing diaphragm. The arch rib segments are sealed and pressurized with air at 8 psi. If the pressure inside the sealed chamber drops by more than 1.5 psi from the 8 psi, then the reason for the air leak should be investigated.

4.6 Connection of Bracing to Rib

There are no access openings in the arch ribs to facilitate installing and tightening the bolts connecting the arch braces to the arch rib webs. Therefore, during fabrication, nut cover cups were welded to the arch rib webs at the brace connection with galvanized nuts installed inside the nut cover cups. The cups prevent the nuts from rotating while tightening the bolts. See Fig.13.

4.7 Unique Foundation System

In true arches, the thrust is taken by the foundation supports, such as the piles. In tied arches, the thrust is taken internally by tie beams. There is no redundancy in case of a failure of the thrust resistance. For this modified tied arch, the longitudinal arch thrust is resisted by multiple foundation elements: the longitudinal foundation ties, the transverse foundation ties and battered piles. The concrete foundation ties, buried beneath Telegraph Road, are sized so that the tensile strength of the concrete is sufficient to carry the arch thrust. However, should the concrete crack, there is adequate reinforcement in the tie. There is also 4" diameter open ducts cast in concrete ties. At present, these are capped but the tie can be post-tensioned if deemed necessary. In addition, batter piles and massive earth pressure against the foundation also assist arch thrust.

Figure 13 : Nut cover cup welded to arch rib

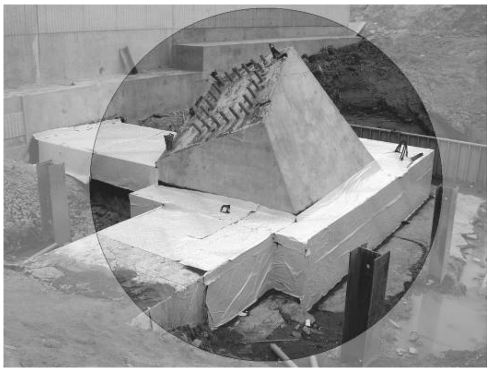

Figure 14 : Longitudinal and transverse foundation ties

5 CONSTRUCTION

5.1 Erection of Ribs and Beams

Each bridge contains approximately 1.56 million pounds of steel. Each arch rib was fabricated into three segments. Prior to welding of the arch, a full lay down shop assembly was performed for the entire arch rib and bracing assemblies. For each bridge, four temporary towers were designed and constructed by the contractor to support the ribs during field assembly. Each outer rib segment was supported at two points, one located on the temporary tower and the other at the pedestal. The temporary towers consisted of an EFCO steel formwork system, with a 100 kips capacity per leg of the tower. The steel framework was supported on EFCO tower foundation mat of hardwood timbers. For the tower stability during rib erection, each tower was anchored to the ground using four helical GUY anchors. A hydraulic jack oriented along the vertical axis of the arch rib was located at each support point on the towers to facilitate adjusting the location of the arch rib into its final location. During erection, the rib segments were twisted into place at a 65-degree angle and then bolted together in the field. The traffic under the bridge was closed and detoured during the erection of the arch segments.

Figure 15: Erection of center rib with temporary towers

After the interior and exterior arch ribs were erected and braced together using the five braces, the shoring towers were removed, and the temporary shoring for the 100 ft long transverse beams are set in place. A total of twenty 120 kips capacity EFCO super stud systems were used to support the transverse beams. At locations where the transverse beams are over Telegraph Road traffic lanes, temporary beams that were supported on the shoring towers were used to support the transverse beams over the traffic lanes. The steel framework was supported on an EFCO tower foundation mat of hardwood timbers. Each transverse beam was supported at two points. A hydraulic jack was located at each support point on the towers to facilitate adjusting the location of the transverse beams into its final location. Before erection of transverse beams, the contractor installed the bearings at each abutment. Transverse beams were erected in four stages.

At each stage, transverse beams were erected first, and then stiffening girders and stringers within the stage were set in place. The stiffening girders were tied-down to the abutments in order to prevent any uplift of the girders during the deck pour. After the erection of the beams was completed, the contractor installed the hangers in place.

The transverse beams were set to the target elevations using the jacks under the beams. The hangers were then pre-tensioned in the sequence and according to the force shown on plans. The pre-tensioned force was equal to the force required to transfer the weight of the steel from the shoring towers to the arch ribs through the hangers.

5.2 Bridge Deck

The original design required shoring during casting of the deck. This cautious method is expensive but less risky. The contractor chose to cast the concrete deck with hanger assembly carrying the load. With careful management and construction procedures, the deck was completed successfully.

6 COST

Cost of the project was a major concern. The engineer's estimate during the planning phase was $7.5 million per bridge. During the design various decisions were made to make the structure redundant and cost of the structure was increased to $8.25 million. With efficient detailing and optimization, the engineer's estimate before bid was reduced to $6.75 million per bridge. At the completion of the construction, the actual construction cost was $6.95 million per bridge. Fig.16 shows the final breakdown of the cost elements.

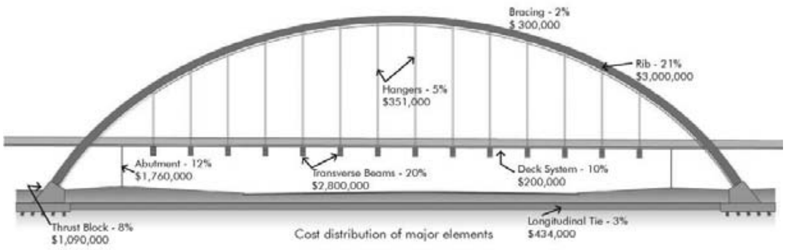

Figure 16 : Cost distribution of major elements

7 SCHEDULE

Due to a shortage of materials, the schedule of this project was greatly impacted. However, the designers, fabricators and erectors, with the assistance of the client, shortened the design and construction time. See Fig.17.

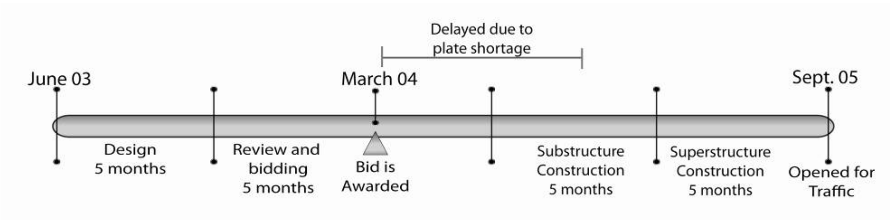

Figure 17 : Project timeline

8 CONCLUSION

The Gateway Bridge, as it is now called, is a signature structure with unique features. It combines the beauty of true arch with the efficiency of tied arch. The design enhances safety with underground tie beams, redundant hangers and redundant foundation systems. The operation is simplified by having pressurized rib boxes and pressurized transverse beams.

Using a value engineering approach to identify functions of elements, estimating function cost and performance comparison of alternatives was developed. This resulted in the elimination of mismatches and produced high value.

9 ACKNOWLEDGEMENTS

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