Construction of Laboratory and Field Demonstration Modified Beam-in-Slab Bridges

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ABSTRACT

Repairing/replacing deficient bridges is a major challenge for transportation system managers and is magnified for Low Volume Road (LVR) systems where inadequate structures need replacing due to structural and functional deficiencies. To maximize limited replacement funds, some local governments employ in-house forces to reduce construction costs, however most lack the resources to construct traditional bridge systems.

The beam-in-slab bridge (BISB) system is a cost competitive alternative designed specifically for LVR systems. Consisting of W sections spaced 24 in. (640 mm) on centers and filled with concrete, the BISB system has been shown to be a sound replacement option, but however in some instances it is not structural efficient. To improve efficiency, composite action was obtained with an alternative shear connector (ASC); a transverse arch was utilized to distribute the wheel loads and reduce the self-weight. Both the section spacing and depth were increased resulting in the Modified Beam-in-Slab Bridge (MBISB) system.

A full-scale laboratory test bridge (L = 31 ft. (9.45 m), W = 20 ft. (6.1 m)) was constructed to quantify the construction process, load distribution and failure modes of the MBISB. Unique to the construction was the transverse arch between the longitudinal girders formed with custom rolled re-useable formwork and minimal deck reinforcement.

A MBISB demonstration bridge (L = 70 ft. (21.34 m), W = 32 ft. (9.75 m)) was designed and constructed without the use of specialized equipment in Tama County, Iowa. The bridge will be load tested in the summer of 2003 to compare its behavior with predicted values.

Key words: beam-in-slab bridge—composite action—low volume road bridge—replacement alternative

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INTRODUCTION/PROBLEM STATEMENT

In Iowa, county governments are charged with maintaining and replacing bridge structures on the off system roads. Off system roads are those roads not cared for by Federal, State, or City forces; since Iowa is a rural state, a majority of the off system roads are also LVR (Low Volume Roads) with far less than 400 ADT (Average Daily Traffic). As reported by the National Bridge Inventory, approximately 30% of the 19,949 bridge structures found on Iowa's off system roads are either structural deficient or functionally obsolete *(1)*. County governments, and more specifically, county engineers are faced with the challenge of upgrading or replacing deficient structures. Due to limited resources and the costs associated with maintaining an aging and deteriorating bridge population, county engineers have expressed an interest in innovative methods to extend available replacement funds.

Many counties in Iowa employ full time bridge crews to maintain and repair deficient structures. However, due to the advanced levels of deterioration and functional obsolescence, replacement is sometimes the most cost effective solution. Constructing traditional bridges is sometimes beyond the capability of some county bridge crews; such designs contain features, such as Traffic Level Four (TL-4) barrier rails that are not required for LVR applications *(2)*. As a result, alternative bridge replacements specifically designed for a LVR application have been investigated.

While not being exposed to high traffic volumes, structures found on LVRs are subjected to heavy loads due to agricultural and off road equipment and must therefore still meet strength and serviceability conditions similar to on system structures. The Iowa State University Bridge Engineering Center, in conjunction with the Iowa Highway Research Board, and numerous Iowa county engineers for several years have been working to develop various alternative bridge replacement designs for LVR.

Beam-in-Slab Bridge System (BISB)

One of the more successful and widely used alternative replacement designs is the BISB system, a design originating in Benton County, Iowa in the mid-1970's. There are approximately 80+ of these structures in service today and more are being constructed, (Lyle Brehm, former Assistant Benton County Engineer, unpublished data). The original BISB design consists of simply supported W12 x 79 girders spaced 24 in. (610 mm) on center. Steel confining straps are welded to the bottom flanges at the longitudinal quarter points to provide confinement during the placement of the concrete. Plywood "floor" formwork rests on the top of the bottom flanges, leaving space between the web and the formwork allowing for the concrete to be in contact with the bottom flange. Concrete fills the void and is struck off even with the top flange completing the BISB system; a typical BISB cross-section is presented in Figure 1.

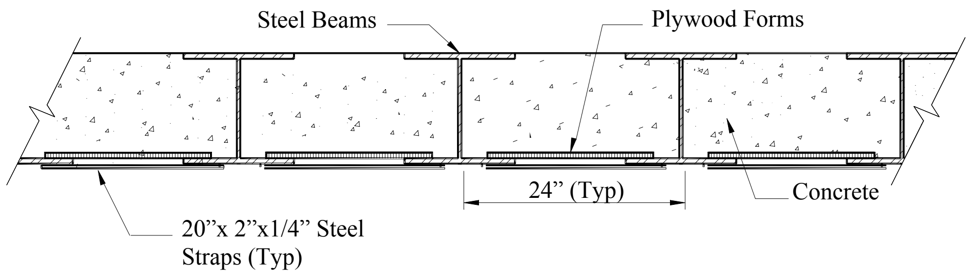


FIGURE 1. Typical Cross Section of BISB

The system is simple to construct with in house forces and does not require the use of specialized equipment. When comparing the costs of the BISB to more traditional systems, a savings of over 20% is possible (Tom Schoellen, Assistant Blackhawk County Engineer, unpublished data). The structural behavior and capacity of the BISB has been studied and verified to be sufficient for Iowa legal loads through both field and laboratory testing completed by Iowa State University researchers (*3*), (*4*).

In spite of the positive qualities of the original BISB system, the design's applicability is limited due to several structural inefficiencies. This includes a large self-weight due to the volume of concrete filling the space between beams and a lack of composite action between the steel girders and the surrounding concrete.

OBJECTIVE

Two major modifications were proposed for the original BISB design in an effort to improve the overall structural efficiency while at the same time maintain its simplicity of construction. The first proposed improvement was to gain composite action between the steel girders and the surrounding concrete increasing the flexural rigidity of the section. The second proposed improvement was to remove the ineffective concrete from the tension side of the flexural section. The combination of integral action and reduced self-weight will allow for deeper girder sections, wider girder spacing and longer overall spans.

Developing Composite Action/ASC

Developing composite action was the first proposed improvement; the standard method of obtaining composite action in steel girder/concrete deck bridges is through the use of shear studs. Applying shear studs requires the use of a specialized welder, a piece of equipment that most counties lack. Thus, the development of an alternative shear connector that can be readily implemented by county forces was undertaken at Iowa State University

After extensive testing, a satisfactory Alternative Shear Connector (ASC) was developed (3), (5). The final design for the ASC consists of 1 1/4 in. diameter holes that are either torched or drilled through the web of a girder (see Figure 2). The holes are centered one diameter below the bottom of the top flange and set on a 3 in. longitudinal spacing for the length of the girder. The method of constructing the holes for the ASC was part of the original investigation. Both torched and drilled holes were investigated, and minimal difference was found between the methods of construction.

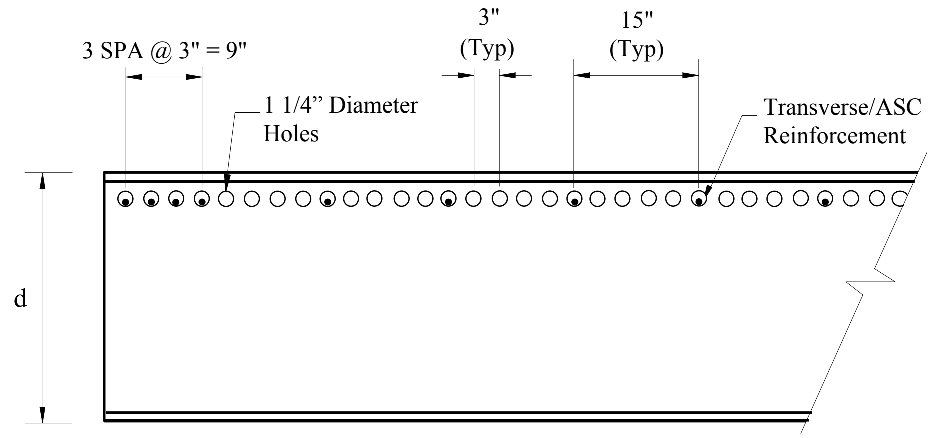


FIGURE 2. Typical Layout of the Alternative Shear Connector

Concrete flows through the holes in the web forming dowels to provide a mechanical connection between the slab and the girders. Transverse reinforcement is required through every 5th hole to provide lateral confinement of the shear dowels (5).

The ASC thus requires the concrete to be below the top flange and in contact with the web, ruling out the use of traditional steel girder/concrete deck forming systems. However, this method of obtaining composite action is readily applicable to the BISB system where the concrete is placed between the girders and is in direct contact with both flanges and the web.

Reducing Self-weight – Transverse Arch.

The span length of the original BISB system is limited by the excessive self-weight of the concrete that fills the void space between the girders. In addition, all the concrete on the tension side of the neutral axis does not contribute to the flexural strength. Thus, a design feature to reduce the self-weight while allowing for an increased girder depth, spacing and span length was desired. A transverse arch, resting on the bottom flange removes a large portion of the ineffective concrete. In addition to reducing the self-weight of the section, the transverse arch allows for a reduction in the deck reinforcement because of the resulting arching action.
Testing the Modifications

Four laboratory specimens were designed and constructed to test the proposed modifications and develop construction guidelines for future bridges. The objective of constructing and testing the four specimens was the quantification of the following parameters:

- Ultimate strength of the arched section
- Failure mode of the section
- Load distribution

- Ease of construction

All the laboratory specimens were constructed from recycled W21 x 62 girders and were outfitted with the ASC to gain composite action. An oxy-acetylene torch was used to construct the ASC holes. In the first three specimens, the only reinforcement was the transverse reinforcing steel needed for the ASC; in the 4th specimen, a layer of #3 reinforcing steel was placed transversely across the girders to prevent possible spalling over the embedded girders. Transverse steel straps were welded to the bottom flanges of the girders in all the specimens to restrain the girders during concrete placement and loading.

Forming the transverse arch posed a challenge because the formwork system needed to be structurally sufficient to support the plastic concrete, remain cost effective and preferably be both removable and re-useable. Several materials and geometric configurations were investigated as possible formwork systems.

POLYETHYLENE PIPE

Polyethylene drainage pipe was used as the formwork for the first arched laboratory test specimen (Figure 3a) *(5)*. Since the girder spacing was 42 in. (1,067 mm), the formwork was made from a section of 42 in. (1,067 mm) diameter pipe. The circular section reduced the amount of concrete needed by 36% and was freestanding. Similar to the plywood in the original BISB, the polyethylene pipe was a single use, stay in place formwork system. For larger girder spacings, polyethylene pipe is not an effective option due to increased material costs and limited geometries.

Arched Plywood

Arching plywood between the girders was investigated as a possible formwork system. This was attempted with W21 x 62 girders spaced 72 in. (1,830 mm) apart with minimal success (Figure 3b). Two layers of plywood with a thickness of 1/4 in. (6.4 mm) each were tested to see if a structurally adequate arch shape could be obtained. In spite of previous testing and analytical modeling, when filled with concrete, excessive deformations required the formwork to be shored, ruling out arched plywood as a possible formwork solution.

Culverts

Corrugated Metal Pipe (CMP) was used successfully as the arched formwork for a demonstration bridge not addressed in this paper. The girders were spaced 24 in. (610 mm) on center requiring a minimal span of 18 in. (457 mm). A 24 in. (610 mm) diameter, 16 gauge CMP was cut into thirds and placed between the girders, removing 17% of the concrete needed between the girders. The CMP was a single use stay in place corrosive formwork system; such systems do not follow standard Iowa Department of Transportation practice.

Custom Rolled Steel Sections

Circular sections, while readily available, are not the most efficient shape especially at larger girder spacings and are limited to standard sizes; thus, an alternative to the circular section was sought.

CMP is rolled from 25 1/2 in. (648 mm) wide steel sections and then riveted together to form the pipe. Based on this procedure, the concept of custom rolled arched steel formwork sections was developed. Two designs were chosen (small radius specimen and large radius specimen) and test specimens of each configuration were constructed to confirm the analytical analysis of the sections.

The small radius (15 in. (380 mm)) formwork for W21 x 62 girders spaced at 72 in. (1,830 mm) was constructed from 14 gauge galvanized steel with a 2 2/3 in. (67.5 mm) x 1/2 in. (12.7 mm) corrugation pattern. The large radius (27 in. (661 mm)) formwork specimen for W21 x 62 girders spaced at 72 in. (1,830 mm) was also made from 14 gauge galvanized steel with the same corrugation pattern.

The large radius formwork removed 45% of the concrete needed to fill the section while the small radius formwork removed over 52% of the concrete volume resulting in a significant reduction in self-weight and material. The sections were made to be recoverable and thus could be used in other bridges. Upon the selection of the formwork system, the specimens were designed, constructed and tested.

First Arch Specimen

A cross section of the first specimen is presented in Figure 3a. Following the original BISB design, the top flanges of the girder were exposed and used to strike off the concrete. The first specimen had the following properties: two girders on 42 in. (1,067 mm) centers, a length of 33.5 ft (10.21 m), and polyethylene pipe formwork. A single point load was applied at the center of the simply supported specimen to model a worst-case wheel loading.

The steel girders began to yield at a load of 126 kips (560 kN), indicating that the arched deck had a higher capacity than the girders in flexure. To investigate the punching shear capacity of the arched deck, the girders were blocked up and the specimen was reloaded. After blocking, the specimen failed in a splitting/punching shear mode when the bottom flange straps failed at a load of 177 kips (787 kN) *(5)*.

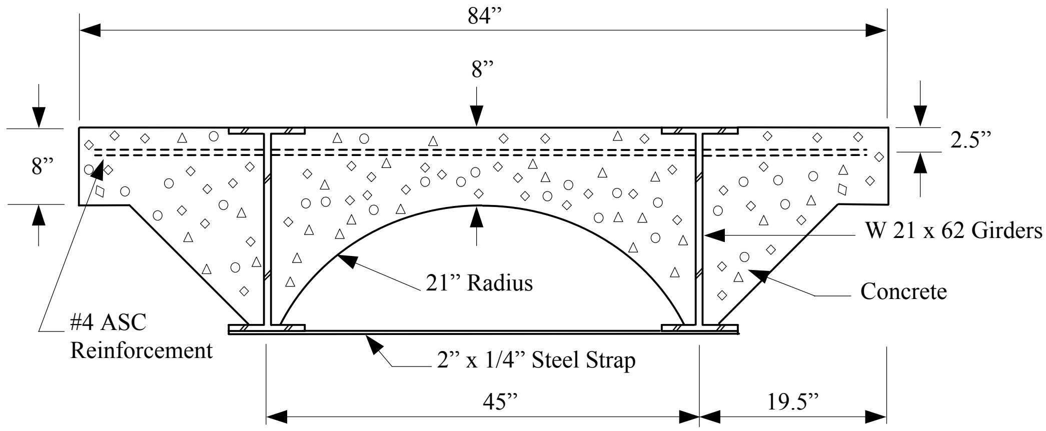
Second Arch Specimen

A cross section of the second specimen is presented in Figure 3b and has the following properties, two girders on 72 in. (1,830 mm) centers, a length of 14.5 ft (4.42 m), and arched plywood formwork. The girders were fully embedded with 3 in. (76 mm) of cover over the top flanges. This modification was made to lower the transverse steel, increase the moment of inertia of the section and provide for a more skid resistant deck. The simply supported specimen was subjected to a single point load at the center of the specimen simulating a worst-case wheel loading.

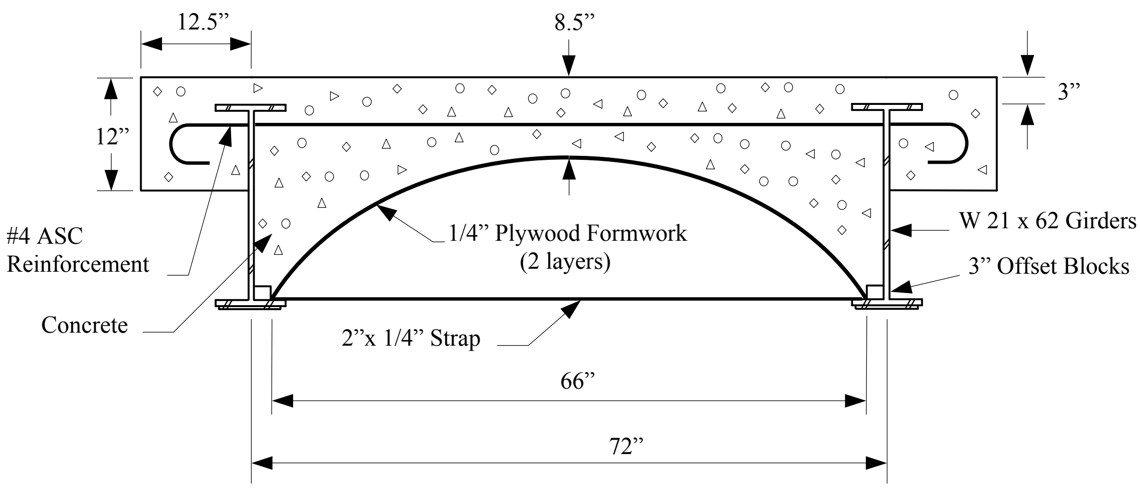
The short clear span was selected to force a punching failure mode prior to the girders yielding in flexure. The second specimen was tested similarly to the first and at an ultimate load of 155 kips (758 kN) a splitting/punching shear failure occurred in the deck when a bottom flange strap failed.

Third Arch Specimen

The third specimen was constructed to investigate improvements based on the results of the first two specimens. Large radius custom rolled corrugated steel sections were used as the formwork since the arched plywood did not perform adequately. A photograph of the third specimen being tested is presented in Figure 4. The third specimen had the following properties: two simply supported girders set on 72 in. (1,830 mm) centers and a length of 14.5 ft (4.42 m). A single point load was applied at the center, similar to the first two specimens.



(a) Cross section of the first arched specimen, polyethylene pipe formwork



(b) Cross section of the second arched specimen, arched plywood formwork

FIGURE 3. Arched Deck Specimens 1 and 2

The corrugated steel formwork, which was removed prior to testing, performed flawlessly and became the preferred formwork system. Larger confining straps were used on the third specimen and a punching failure occurred at 260 kips (1,157 kN). This test provided assurance that the transverse arch section in combination with the ASC provided for a sufficiently strong system with the capacity to resist legal Iowa loads.

To this point, only single bay specimens had been constructed and tested in an effort to quantify the capacity and mode of resistance of the composite transverse arched section. The previous specimens provided minimal information on the behavior of the section in an actual bridge application where load would be distributed to adjacent bays. A fourth specimen was designed and constructed to obtain distribution data as well as ultimate strength data on the composite arch system when it was used in a bridge.

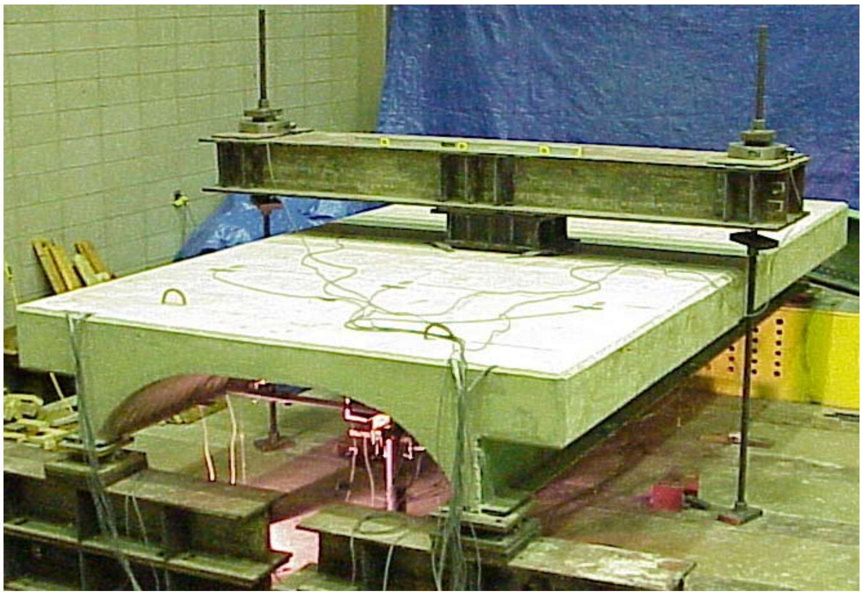


FIGURE 4. Test Setup for the Third Arched Specimen

Fourth Arched Specimen

The fourth specimen consisted of four simply supported girders on 72 in. (1,830 mm) spacing, forming three monolithic bays. The overall dimensions of the specimen were L = 31 ft (9.45 m) W = 20 ft (6.1 m). Small radius custom rolled steel sections were used for the formwork. An overall view of the specimen during construction with the arched formwork in place is presented in Figure 5a. The finished structure with the service level loading system in place is presented in Figure 5b.

(a) Formwork and reinforcing before concrete placement (b) Typical service level loading setup

FIGURE 5. Construction and Service Level Koading of Specimen 4

The specimen was subjected to service level loads representing a single wheel load at several locations. The load was applied at six loading points transversely across the structure at the 1/4 span and the midspan plus three load points at the 3/4 span to quantify the lateral load distribution. Two series of service level tests were performed, the first with the confining straps in place and the second with the confining straps released. It was found that at service level loads, releasing the transverse straps had little effect on the behavior of the structure.

Midspan deflections due to a concentrated load placed at the mid point of the specimen are presented in Figure 6. For this load configuration it can be observed that the difference between the straps being in place or removed has a minimal effect; the largest change in deformation for this load case was 0.009 in. (0.23 mm). The displaced shape also indicates a reasonably symmetric transverse load distribution. The largest difference in deflection for any of the service load cases was approximately 0.018 in. (0.46 mm).

The arched specimen also exhibited excellent lateral load distribution under the service level load. For the load case represented in Figure 6, the maximum percentage of the total load carried by a single interior girder is 32% based on the moment fraction calculated from strain data due to flexure. This result is significantly less that the 40% calculated for an interior girder subjected to a single lane loading based on the 1994 AASHTO LRFD Bridge Specification for beam and slab decked bridges *(6)*.

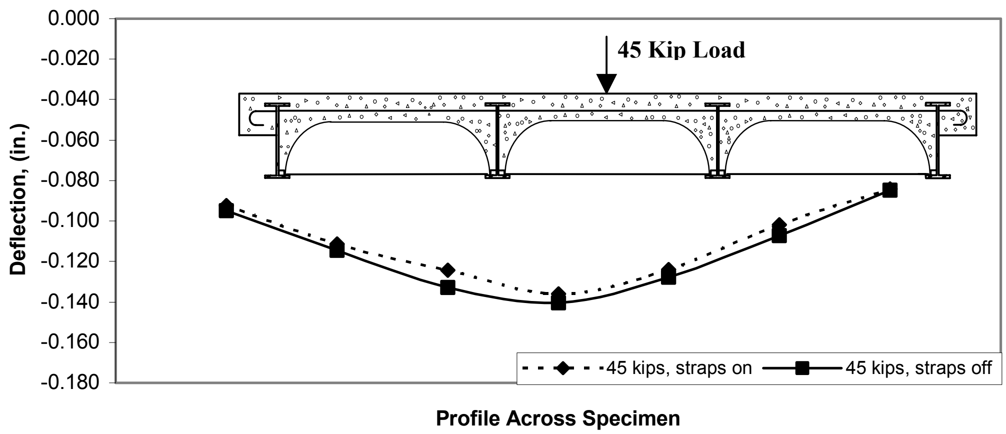


FIGURE 6. Plot of Midspan Deflections with and without Confining Straps

Upon the completion of the service level tests, the specimen was subjected to ultimate loading. The specimen failed in flexure with the longitudinal girders yielding and deflecting to a maximum of 7.1 in. (180 mm) at a load of 302 kips (1,343 kN) prior to the termination of the test. The data gathered and observed behavior of Specimen 4 under service and ultimate loading provided verification that the modifications to the original BISB had more than sufficient strength to be used in a field application. A demonstration bridge utilizing both modifications was first designed and then constructed.

MODIFIED BEAM-IN-SLAB DEMONSTRATION BRIDGE

Design

The design of the demonstration bridge followed the 1994 AASHTO LRFD Bridge Specification (6). The structure was designed to meet applicable strength and serviceability requirements for an HS-20-44 design vehicle. To ensure a conservative design for the first bridge of this type, the steel girder/concrete deck slab load distribution factors were used to calculate lateral load distribution to the girders.

Six W27 x 129 Grade 50 steel girders spaced 72 in. (1,830 mm) on center with the ASC were required for the 70 ft. (21.34 m) span. Custom rolled corrugated formwork with a radius of 20 1/2 in. (521 mm) were constructed to form four of the five bays. The remaining bay was formed by modifying and reusing small radius formwork sections used in Specimen 4 (laboratory bridge).

Two lines of diaphragms of recycled S18 x 55 sections were placed at 24 ft (7.31 m) from either end of the structure. The diaphragm spacing was necessary to prevent instability during the placement of the concrete deck. In order to obtain the needed development length in the transverse ASC reinforcement, a custom exterior formwork system was also designed.

Construction

Construction of the demonstration bridge followed the traditional steel girder/concrete slab bridge construction format. Upon the completion of the abutment system, the cambered girders, complete with a drilled ASC, were fitted with diaphragm and exterior formwork brackets and 'swung' into place (Figure 7a). Transverse crown was introduced to the structure through the use of steel bearing pad of staggered thickness. The diaphragms were installed and a concrete backwall system placed, leaving placement of the arched formwork as the next step.

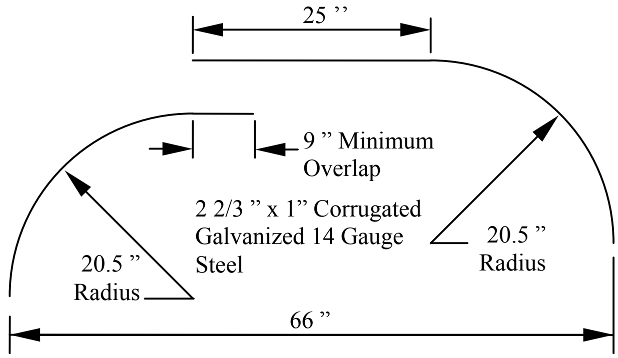
The custom rolled corrugated sections were assembled offsite prior to the arrival of the girders. A local culvert manufacturer rolled the sections to the specifications indicated in Figure 7b. The assembly process took the following sequence. The two partial sections were assembled into one piece by bolting the individuals together with 5 – 1/4 in. x 3/4 in. (6.25 mm x 19 mm) Grade 5 cap screws. The individual arched sections were then fitted together and bolted into 10 ft. (3.05 m) long segments and stored at the ISU Structures Laboratory. The completed segments were transported to the job site and placed directly into the bridge. Figure 7c documents the assembly of typical segments and Figure 7d gives a clear view of installing the segments. The segments of formwork were blocked into place using wooden spacer blocks and shimmed tight to the diaphragms and backwalls completing the interior formwork.

The structural reinforcement required in the transverse arched section, and additional temperature and shrinkage reinforcement was then set in place. The exterior formwork was set into place and a leveling rail installed to set the grade for the power screed to complete the bridge formwork.

After the concrete was placed and cured and a thrie beam guardrail system was installed, the bridge was opened to traffic. The completed structure can be viewed in Figure 8a. Four months after the concrete placement, county crews removed the custom rolled formwork leaving the underside of the Modified Beam in Slab Bridge readily viewable (see Figure 8b).

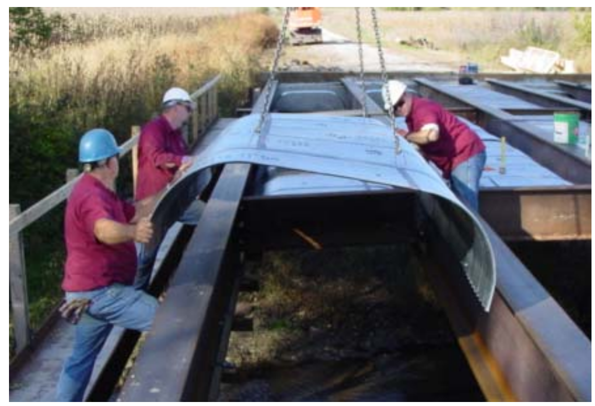
The structure was constructed completely by in house forces with a cost savings of approximately 10% in comparison to completing traditional structures. Field testing of the demonstration bridge is scheduled for mid-July 2003.

(a) Setting the girders into place



(b) Custom rolled corrugated arches

(c) Assembling the segments



(d) Setting the arches into place

FIGURE 7. Setting the Girders and Constructing the Arched Formwork

(a) Finished MBISB Demonstration Bridge

(b) Removing the arched formwork

FIGURE 8. Completing the Construction of the Demonstration Bridge

SUMMARY/CONCLUSIONS

The original BISB design has served as an alternative replacement design for LVR in Iowa for over 25 years. The system can span openings of up to 50 ft (15.24 m) and both field and laboratory testing have verified the design as structurally adequate for legal loads. The system is simple to construct and requires minimal equipment. However, due to excessive self-weight, the system is limited in span, girder size and spacing.

Two modifications, the ASC and the transverse arched section, were proposed to improve the overall efficiency of the structure. It was hypothesized that the modifications would allow for a deeper girder sections, wider girder spacing and longer spans while making better use of materials. Research was undertaken to investigate the applicability of the modifications.

Four laboratory test specimens were constructed and tested to evaluate the performance of the modifications. Three single bay specimens were constructed to study the structural behavior of the transverse arch. Results from the three specimens suggested the system was applicable to a bridge application and implicated the custom rolled sections as the formwork system of choice. A 3-bay specimen was constructed to investigate the lateral load distribution and flexural behavior of the combined modifications in a bridge system. Results from service level loadings indicated superior load distribution and ultimate testing results provided evidence that the MBISB system could easily support Iowa legal loads.

With the success of the laboratory testing program, a demonstration bridge was designed and constructed utilizing both of the modifications. The resulting structure was constructed solely by county forces and resulted in a cost savings for the county government. The structure has been in service for seven months and will be load tested this summer.

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DISCLAIMER

The opinions, findings, and conclusions expressed herein are those of the authors and not necessarily those of the Iowa DOT or the Iowa Highway Research Board.

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