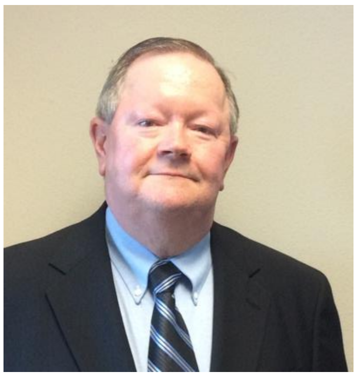
MODULAR STEEL SUPERSTRUCTURES FOR ACCELERATED BRIDGE CONSTRUCTION - IOWA DOT CASE STUDIES



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BIOGRAPHY

Norm McDonald is the director of the Office of Bridges and Structures for the Iowa Department of Transportation. He has worked for the Bridge Office for 30 years with the last 15 years as State Bridge Engineer. Mr. McDonald is responsible for directing the design and inspection of structures on the primary system. His experience includes the development and design of new structures and the load rating and inspection of existing structures. Mr. McDonald is a member of the Executive Committee for the AASHTO Subcommittee on Bridges and Structures. He Serves as the Chairman of the Technical Committee for Structural Steel Design (T-14), the Vice-Chair of the Technical Committee for Structural Supports for Signs, Luminaires, and Traffic Signals (T-12), and is a Region 3 member on the Technical Committee for Bridge Preservation.

Curtis Carter is a Transportation Engineer Specialist in the Bridge Final Design Section of the Iowa Department of Transportation Office of Bridges and Structures. Mr. Carter’s 6 year work experience with the DOT has included design responsibility on over 40 new bridge, bridge replacement and bridge repair projects.

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SUMMARY

Structural steel has played a contributing role in the overall success of several recent accelerated bridge construction (ABC) projects in the State of Iowa. Notably, Iowa DOT found the use of structural steel to be particularly advantageous to two recent ABC projects in Pottawattamie County. Utilizing rolled steel, decked beam modular superstructure design, the Keg Creek and Little Silver Creek projects were successfully completed during 2 week and 3 week accelerated road closure periods, respectively.

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Introduction

In the interest of seeking ways to better serve the traveling public, and to develop technological capabilities consistent among the nation's leaders in accelerated bridge construction (ABC), the Iowa Department of Transportation (DOT) has completed a series of demonstration projects showcasing a variety of accelerated bridge construction processes. These ABC demonstration projects have provided the Department with the opportunity to assess the viability of numerous accelerated construction strategies, and to cultivate the experience necessary to support sound policy decisions and successful implementation of ABC practices.

Various accelerated construction methods have been employed as a part of the Department's ABC demonstration program, but among the few techniques selected for repeat demonstration has been the modular method for superstructure construction. First demonstrated in Iowa on the Keg Creek bridge replacement project in 2011, this construction concept was again successfully deployed on the Little Silver Creek bridge replacement project in 2015.

Modular Concept

Modular construction has been characterized in Iowa by the use of prefabricated, decked beam superstructure elements as the primary means to accomplish a bridge project's accelerated schedule objectives. The prefabricated superstructure elements, referred to as modules, are constructed off site and in advance of the critical bridge construction activities. Each module represents a fully assembled fraction of the final completed bridge superstructure, and multiple modules are assembled and connected adjacently to establish the desired length and width of bridge superstructure.

Figure 1:
Modular Bridge Construction

Iowa DOT Modular Bridges

US-6 over Keg Creek

Iowa DOT's experience with the modular construction technique initiated with a showcase project developed as a part of Transportation Research Board (TRB) Strategic Highway Research Program 2 (SHRP 2). The objective of SHRP 2 Project R04 was to "develop standardized approaches to designing and constructing complete bridge systems for rapid renewals".

The SHRP 2 showcase demonstration, located on US Highway 6 over Keg Creek in Pottawattamie County, featured replacement of an existing structurally deficient and functionally obsolete bridge with a new, rolled steel beam structure using the modular construction method. The new three-span, 0° skew, 204'-6 x 44'-0 bridge was successfully constructed during a scheduled 2-week road closure in 2011.

IA-92 over Little Silver Creek

Following the success of the US-6 over Keg Creek project, Iowa DOT engaged in a subsequent demonstration of the accelerated modular construction technology. Focused this time on investigating how specific ABC design features might be adapted and standardized for more mainstream application on the State Highway System, this project included second-generation construction details evolved from the lessons learned on the prototype Keg Creek demonstration.

This second demonstration project included replacement of a structurally deficient bridge, located in Pottawattamie County on IA Highway 92 over Little Silver Creek, with a new, rolled steel beam structure. Although similar to the Keg Creek project in general scope and situation, the Little Silver Creek project featured the additional design challenges of longer spans, skewed alignment, and significant vertical curvature. The replacement bridge was a three-span, 20° skew, 234'-0 x 44'-0 structure built using the modular construction method during a scheduled 3-week road closure in 2015.

Figure 2:
US-6 over Keg Creek Bridge

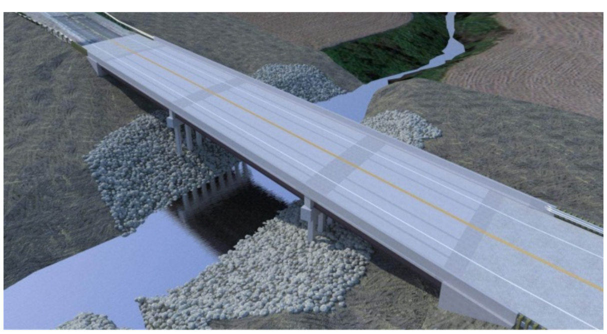

Figure 3:
IA-92 over Little Silver Creek Bridge

Design Approach

A primary design objective of the Iowa DOT projects was to maintain the size of the modules within the conventional handling limits of typical bridge contractors operating in the state. Conscientiously controlling the maximum size and weight of superstructure modules would help foster a competitive bidding process by accommodating the use of conventionally-sized and readily available construction equipment.

Per discussion with the Iowa Association of General Contractors, practical maximum module weights were set at approximately 120,000 pounds, with preferred maximum target weights of about 100,000 pounds. Module geometry would be sized for transport on a flatbed trailer, with the expectation that an overweight/oversize permit would be required.

Upon establishment of these geometric constraints, the next design step was to establish the type and size of structural members such that the configuration of superstructure modules could be optimized for rapid constructability. Structural steel was identified as the preferred beam material, largely due to its advantages in strength to weight ratio. Compared to prestressed concrete, the use of steel beams allowed for a reduced percentage of the module weight to be allocated to the beam system, in turn allowing a higher percentage of weight to be dedicated to a wider prefabricated deck system. This permitted the design team to minimize the quantity of modules required and facilitate more rapid construction.

Structural steel also provided the design team with the opportunity to camber specific beam sections as necessary to match the road grade, rather than contend with the generally inflexible and somewhat variable camber associated with prestressed concrete beams. The consistent, reliable and custom-fit shape of the steel beams greatly simplified module fabrication and aided in successful placement and fit in the final constructed condition.

Decked Steel Beam Modules

The individual superstructure modules for Iowa DOT's projects were each comprised of a pair of parallel, single-span rolled steel beams connected with rolled steel channel bracing, supporting a strip of precast reinforced concrete bridge deck.

Each bridge deck superstructure was detailed as an assembly of 18 prefabricated, single-span modules, arranged six wide per span for each of the bridges' three spans.

Rolled Steel Framing

Rolled steel beam section sizes were detailed as W30x99 and W40x149 for the Keg Creek and Little Silver Creek projects, respectively. Center-to-center spacing of the parallel module beam pair was detailed as 4'-6. For handling and setting purposes, the beam bearings at each end of each module were level.

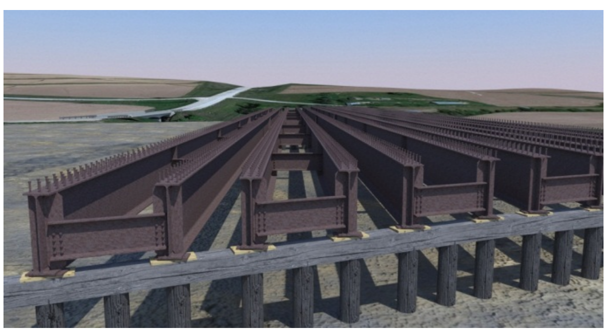

Figure 4:
Typical Rolled Steel Module Framing, Shown on Temporary Falsework

For Keg Creek, the shorter span lengths and tangent vertical alignment allowed for the use of uncambered beam sections. For Little Silver Creek, the longer spans lengths and curved vertical alignment prompted the detailing of cambered beam sections for a better grade match. Bolted rolled steel MC18x42.7 channels were used as the permanent bracing members installed between the paired module beams.

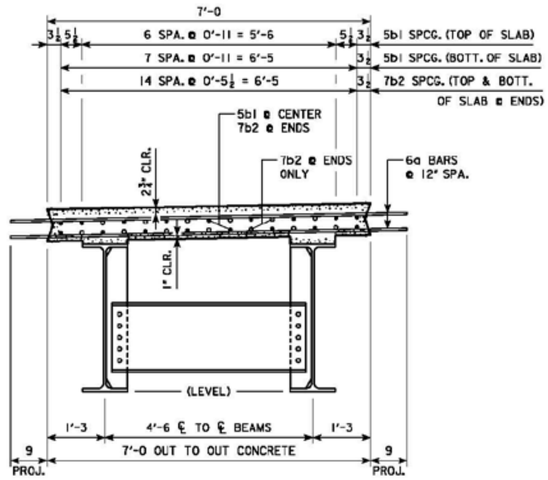

Figure 5:
Typical Decked Beam Module Cross Section

Reinforced Concrete Deck

Consistent with standard policy, both the Keg Creek and Little Silver Creek projects detailed a 2% normal crown cross slope for the completed superstructure. Achievement of the desired deck cross slope was established uniquely for each project's modular system. For the Keg Creek project, the precast deck section was cast perpendicular to the beam webs, essentially squaring the module. The modules were then set on a sloped substructure seat matching the desired 2% deck cross slope. Conversely, with the complicating factors of skew and vertical curvature to contend with on the Little Silver Creek project, the steel framing was squared, but the concrete haunches were varied as required to allow the deck section to be cast on top of the steel framing at the desired grade and cross slope. The Little Silver Creek modules were then set on a level substructure seat, stepped between adjacent modules.

Width and length of the concrete deck sections cast upon the steel module frames varied slightly for each bridge, notably due to differences in the geometry of the closure joint systems used for each project. The thickness of the deck sections also varied slightly between projects. Iowa DOT typically utilizes an 8" nominal deck for standard bridges, but due to the construction tolerances required to accommodate the accelerated modular construction, it was desirable to provide additional sacrificial thickness to the top of the precast deck sections. The sacrificial thickness would accommodate grinding and profile refinement in the event of slight differential grade between adjacent modules. With the Keg Creek project incorporating square modules placed on sloped seats, a sacrificial thickness of ½" was detailed at the top of the deck to allow development of a parabolic crown profile at the center of the deck. The modules for the Little Silver Creek project were more accurately cast to the proposed final grade profile, and a ¼" sacrificial thickness was deemed sufficient.

The modular deck sections were provided with reinforcing steel projected beyond the finished edges of the concrete deck to allow splicing and connection with adjacent modules. The reinforcing steel for the Keg Creek project was epoxy coated for purposes of corrosion protection, in accordance with conventional design policy. Epoxy coated reinforcing steel was also considered for use on the Little Silver Creek project, although the allowable practices specified for joint preparation (aggressive roughening and media blasting) could potentially damage the epoxy coating. Based largely on this reasoning, but also considering the advantages of long-term performance, stainless steel was selected for the deck reinforcing on the Little Silver Creek project.

Module Fabrication

The design plans and specifications for the Keg Creek and Little Silver Creek projects provided the contractor with several options for the fabrication of the superstructure modules. The modules could be fabricated at preapproved facilities specializing in this type of work, or the contractor could elect to fabricate the modules at a site of their choosing, under the general inspection of DOT personnel. The manner in which the modules were to be fabricated was not prescribed, accommodating either assembly line or bespoke-type production methods.

Figure 6:
Module Deck Casting

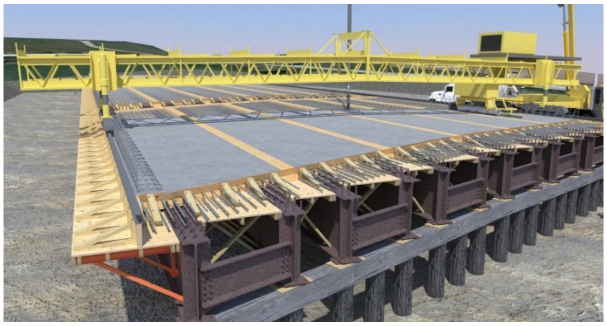

Figure 7:
Module Deck Finishing

Figure 8:
View of Fabricated Modules from Top of Deck

For the Keg Creek project in particular, module geometry was standardized sufficiently such that assembly line production of single modules could be feasible and potentially cost effective. However, the contractor elected to fabricate the steel framework for all the modules concurrently, supported on temporary falsework emulating the final proposed support conditions. The module frames were set in respective position relative to their final intended placement location, and the precast deck sections were cast onto the frame assemblies using conventional bridge deck finishing equipment. The longitudinal and transverse joint openings between modules were accommodated with blockouts installed within the deck forms, and the deck sections for all modules were cast simultaneously with a single concrete placement. Following cure of the concrete bridge deck sections, the deck forms were stripped from the modules, the joint blockouts were removed, and the individual modules were separated for transport and placement. With the success of this fabrication method demonstrated on the Keg Creek project, the contractor again utilized a similar procedure to successfully fabricate the more geometrically complex Little Silver Creek superstructure modules.

Module Assembly

Transport and Placement

As indicated previously, Iowa DOT made it a design objective to size the individual superstructure modules within the transport and handling limits of conventional contractors operating in the state. For the Keg Creek and Little Silver Creek projects, maximum as-built module weights were approximately 112,000 pounds and 100,000 pounds, respectively, and maximum module lengths were about 70 feet and 90 feet, respectively.

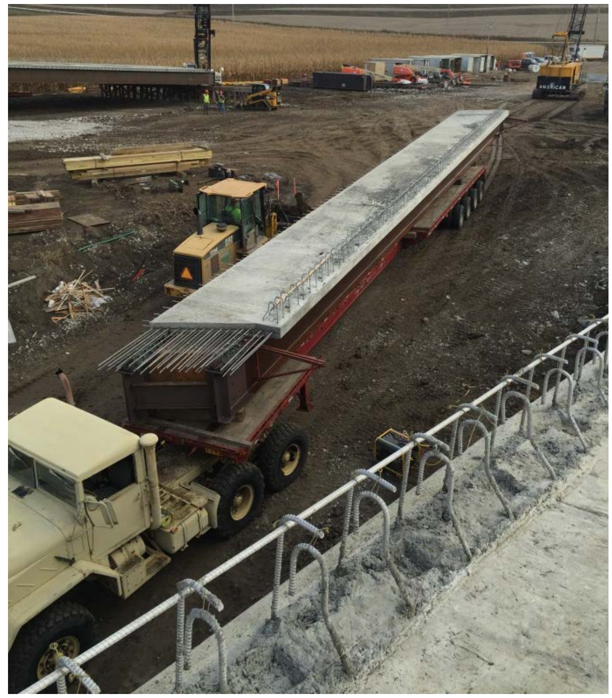

Figure 9:
Typical Module Transport

Figure 10:
Typical Module Lifting

The superstructure modules for both projects were fabricated sufficiently close to the bridge replacement sites such that highway transportation would not be necessary. Off-highway hauling on the order of several thousand feet was needed to relocate the modules to the nearby final placement location. Modules were transported singly from their fabrication site to the placement location by truck and oversized flatbed trailer. Modules were picked using one crane at each end, with two rigging points per crane. The rigging points consisted of structural steel lifting brackets secured to each end of each steel beam within the modular unit. The bridge contractors for each project were able to readily source the necessary cranes from their regular owned/rented inventory, and required crane capacity for these projects was deemed comparable to conventional medium-scale bridge construction projects in the state.

Figure 11:
Module Placement at Keg Creek

Figure 12:
Module Placement at Little Silver Creek

The modules were transported to the final placement site following construction of the new bridge substructures. Given that the modules for each project were constructed on falsework emulative of the final substructure designs, the modules could be relied upon for a match-marked fit when positioned respectively in their final designated locations. Following placement, preparations were made to complete the connections between modules.

Longitudinal Joints

To maximize the amount of bridge deck surface that could be precast, and thereby reduce the time and construction effort required to complete the longitudinal deck connections between modules, the Keg Creek and Little Silver Creek projects utilized ultra-high performance concrete (UHPC) joint systems. Favored for its superior bond and ability to develop reinforcing steel splices over short distances, the use of UHPC could allow for a balance of narrower joint openings and reduced reinforcing steel congestion, as compared to more conventional concrete or grout systems.

The Keg Creek project utilized a 6” wide, keyed longitudinal joint system to develop the reinforcing steel splices between adjacent superstructure modules. The reinforcing steel within the joint consisted of transverse, staggered-lap, closed-end hairpin bars projecting from the superstructure modules, interlaced with longitudinal reinforcing bars threaded through the overlapping hairpins. Although this joint system effectively minimized the amount of UHPC material required to complete the joint closure, the complex and intricate bar placement was identified as relatively difficult to complete within the accelerated construction timeframe. The post-construction review of the Keg Creek project identified opportunities to improve the longitudinal joint system by simplifying the reinforcing steel configuration and relaxing the construction tolerances.

Figure 13:
UHPC Longitudinal Joint - Keg Creek

Following the lessons learned from the Keg Creek project, and leveraging contemporary research findings, the Little Silver Creek project utilized a 10” wide, keyed longitudinal joint system for improved constructability. Instead of closed hairpin bars, open-ended straight bars were used to make the spliced connections, and a wider tolerance was provided for the staggered, non-contact bar laps.

Figure 14:
UHPC Longitudinal Joint - Little Silver Creek

Transverse Joints and Deck Continuity

The Keg Creek and Little Silver Creek projects were designed to accommodate dead load and live load forces under simply supported conditions. However, the project design teams identified several advantages to be gained by providing a transverse restraining connection between adjacent module spans over the piers. Restraining the module ends from excessive rotation would eliminate the need for an expansion joint system over the substructure supports, and the development of live load continuity between spans would also be expected to increase the service capacity of the structure. To provide this restraining connection, each project was detailed with a means to transfer live load tensile stresses at the deck level, and live load compressive stresses at the beam bottom flange level.

For the deck-level tension connection, the design strategy for the Keg Creek project was to rely upon relatively narrow UHPC joints to transversely connect the superstructure modules. Laboratory validation efforts raised some uncertainty regarding the serviceability of this design, particularly with regard to the joint’s bond performance and watertight integrity at such a high-stressed region of the deck. To mitigate these uncertainties, the project was retrofit with a longitudinal post-tensioned detail. Steel brackets were bolted to the upper portions of the beam webs near the ends of each beam line, and post-tensioned threaded rod was installed through to apply a compressive force at the deck-level connection, offsetting a majority of the anticipated tensile stresses resulting from live load continuity over the bridge piers.

In effort to provide a simpler detail, the Little Silver Creek utilized a much wider transverse closure over the pier. This allowed for the placement of additional supplementary reinforcing steel to better resist the live load continuity stresses, and also located the joint interface in a lower-stressed region of the deck. An additional benefit of this wider joint detail was the ability to use conventional concrete materials in lieu of the more expensive UHPC.

Figure 15:
Transverse Deck Closure - Keg Creek

Figure 16:
Transverse Deck Closure - Little Silver Creek

Figure 17:
Bolted Tie and Post-Tensioned Detail - Keg Creek

Figure 18:
Compression Block Detail - Little Silver Creek (Shims not shown)

The beam-level compressive connections were accommodated by providing load paths between the beam ends over the piers. The Keg Creek project detailed a positive connection between beam ends utilizing bolted steel tie plates. In effort to ease construction tolerances, the Little Silver Creek project detailed a fabricated steel compression block, snug fit and shimmed between beam ends. The beam ends and compression block assembly for the Little Silver Creek project were encased within a full-depth concrete diaphragm cast integrally with the deck-level closure using conventional concrete.

Project Cost and Schedule

The contract bid price for the Keg Creek accelerated bridge replacement project was $2.7M, with contract scheduled road closure duration of 14 days. An incentive/disincentive clause was included in the contract ($22,000/day) for completion before or after the scheduled roadway reopening, and actual construction of the project was accomplished in 16 days.

The Little Silver Creek project required comparatively more construction effort during the critical closure period, and also included some proportionally higher material and/or labor costs associated with the stainless steel reinforcing and the more rigorous UHPC joint preparation and forming requirements. The contract bid price for the Little Silver Creek project was $3.6M, and the contract scheduled road closure duration was 21 days. As with Keg Creek, the Little Silver Creek included an incentive/disincentive clause ($9,000/day) to accommodate completion of construction before or after the scheduled road reopening date, and actual construction was accomplished in just over 24 days.

With overall cost per square foot of bridge at approximately $240/sf and $290/sf for Keg Creek and Little Silver Creek, respectively, construction cost per square foot was roughly twice that of conventional bridge replacement projects in the state. However, considering the dramatic reduction in road closure duration attributable to the modular construction procedures, the savings in user cost can be shown to offset a considerable portion of this price premium.

Conclusion

The modular rolled steel decked beam system was found to be an excellent solution for accelerated replacement of the existing deficient bridges at the Keg Creek and Little Silver Creek sites. Leveraging the advantages of structural steel contributed significantly towards the positive outcomes of these projects. In particular, the use of structural steel afforded benefits in design simplicity and weight savings, both of which were greatly advantageous to the accelerated construction process.

Key aspects of these designs included:

- 7'-0 approximate width, single-span decked beam modules supported on rolled steel framework
- Longitudinal deck joints using Ultra-High Performance Concrete
- Transverse closure details designed to develop live load continuity between spans.
- The use of accelerated bridge construction methods.

The Keg Creek and Little Silver Creek projects have demonstrated the viability and adaptability of the modular method for accelerated bridge construction in Iowa. To date, the modular superstructure details used for these projects have proven durable, and in particular, the second generation details are expected to exceed long-term serviceability expectations. The rolled steel decked beam concepts and details used for these projects will remain among Iowa DOT's top choices for future accelerated bridge construction solutions.

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