US 34 OVER THE MISSOURI RIVER: DESIGN & CONSTRUCTION OF A HAUNCHED STEEL PLATE GIRDER WITH SUBSTRINGER BRIDGE

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BIOGRAPHY

Phil Rossbach is a vice president and a senior project manager for HDR Engineering in Omaha, NE. He served as project manager for the US 34 Bridge over the Missouri River. In his 32 years of experience, Mr. Rossbach has been responsible for directing the study and design of numerous bridge and transportation projects. His experience includes project management and design of a wide range of bridges, including steel, prestressed concrete, and reinforced concrete structures as well as inspection and load rating of existing bridges. Mr. Rossbach is a registered Professional Engineer in Iowa and Nebraska and a registered Structural Engineer in Massachusetts.

Dusten Olds is a Professional Associate and Bridge Engineer with HDR Engineering in Omaha, NE. He has served as lead structural engineer on multiple designs and load rating projects. His background includes experience in complex design and modeling as well as load rating of multiple structure types. Mr. Olds received his BS and Masters of Engineering from Washington University in St. Louis along with an MBA from University of Nebraska at Omaha.

Ahmad Abu-Hawash is the Chief Structural Engineer with the Iowa Department of Transportation and has been working with the DOT in highway construction, bridge rating, and bridge design since 1983. He is responsible for overseeing the design of major bridge projects, design policy review, coordination of bridge research, and the resolution of structural fabrication issues. Ahmad received his BS degree from the University of Iowa and his MS degree in Structural Engineering from Iowa State University.

SUMMARY

As part of the efforts to upgrade US Highway 34 to a four-lane divided highway between Iowa and Nebraska, a new 3,276-foot bridge across the Missouri River was required, including a 1,297-foot main navigational unit. The main navigational unit superstructure utilizes a haunched steel plate girder with substringer system. This option was chosen over a steel truss option and a traditional multi-girder system after a preliminary bridge type study was conducted.

Fabrication, shipping and construction of the steel girders was very challenging due to the size of the sections and the intricacy involved with picking, handling, and shipping to the construction site. Additionally, the fabrication of the steel superstructure utilized laser scanning and computer numerically controlled drilling technology to fabricate specific steel pieces.

During final design, AASHTO LRFD approximate equations for live load distribution were compared to the results from a 3D finite element analysis.

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Introduction

As part of the efforts to upgrade US Highway 34 to a four-lane divided highway as it crosses the Missouri River between Iowa and Nebraska, a new bridge across the Missouri River was required in lieu of the narrow 2-lane toll bridge that currently serves as the highway's river crossing through the town of Plattsmouth, NE. The 3,276-foot long structure that is currently under construction was the result of an extensive route location study, environmental impact statement and bridge type study. Scheduled to be completed in 2014, this bridge is comprised of a 1,297-foot long, three-span main unit (391-foot, 515-foot, 391-foot) that uses a haunched steel girder with substringer system, and three prestressed concrete beam approach units. Project geometrics include a tangent horizontal alignment with non-skewed piers along with a crest vertical curve with a high point within the main river span. The cross section of the main river unit consists of five, haunched steel girders spaced at 20'-6" with substringers located in the middle of each bay. Figure 1 shows the typical section and Figure 2 shows the plan and elevation for the main river unit.

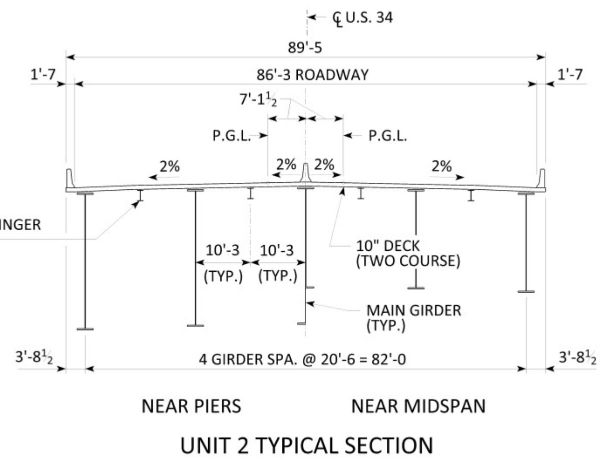

Figure 1: Typical Section - Main River Unit

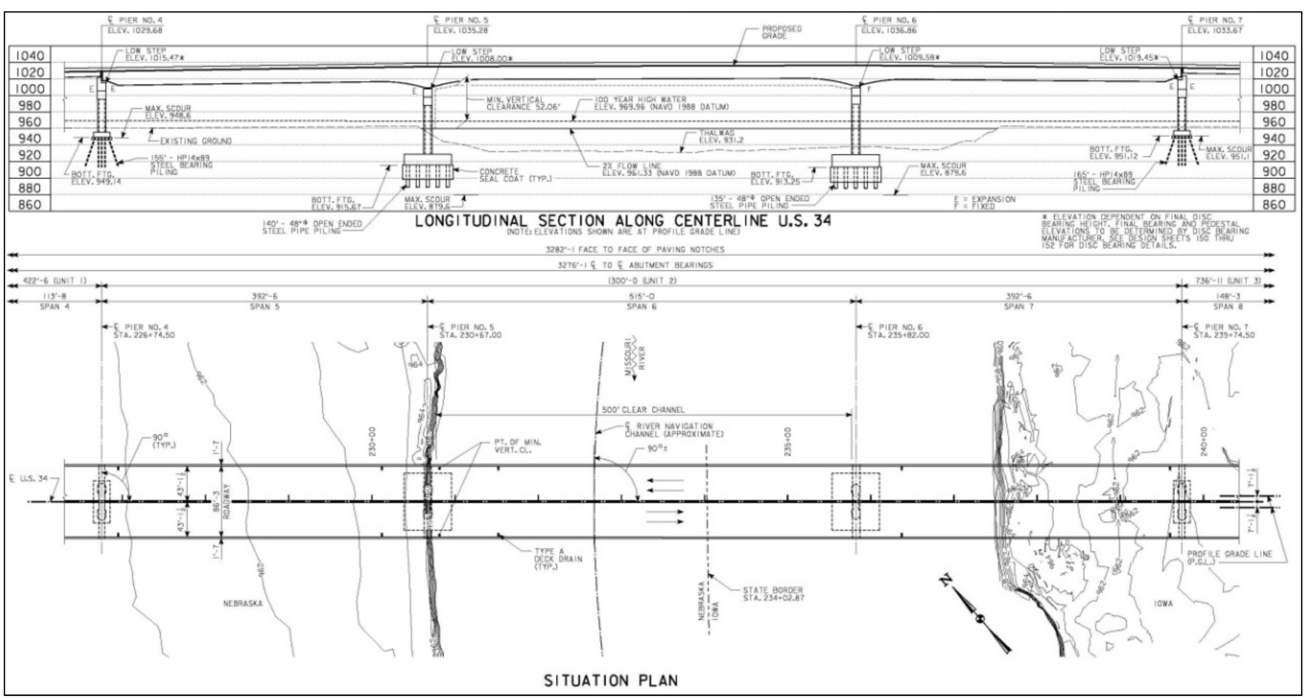

Figure 2: Plan & Elevation – Main River Unit

Preliminary Bridge Type Study

For the preliminary bridge type study, several bridge options were considered. After initial consideration, three options for the main river unit were investigated further: a 3-span haunched steel plate girder option with 8 main girders, a 3-span haunched steel plate girder with substringer option with 5 main girders; and a 3-span constant depth steel truss option. Additional bridge types such as a steel box and concrete segmental box were considered in the conceptual phase but eliminated due to cost and/or owner preferences.

At 515-foot, the main navigation span of the bridge pushed the traditional limits of steel plate girder spans, yet a truss-style bridge had its own issues regarding redundancy, long term maintenance and potentially higher costs. To facilitate the decision making process, HDR developed a cost estimate for each option, including life cycle costs, for comparison. Preliminary analysis was used to determine girder weights for each of the girder options. Additionally, steel fabricators were contacted to discuss relative cost differences between the multi-girder system and the substringer system. The fabricators indicated that the substringer system would be preferable and somewhat less expensive due to the reduced number of plates required to handle and ship. HDR's review of additional structures at these span lengths also showed a predominate preference toward a substringer system. For the truss option, a constant depth Warren truss without verticals was studied due to its efficiency at these span lengths, as well as the clean and modern look to the truss. As before, initial sizing of members was performed and a cost estimate was developed for this option.

For the cost estimate, the plate girder options were assumed to utilize weathering steel while the truss option was assumed to utilize a painted system. Local contractors were contacted to help determine erection costs for each option. Their input resulted in a ten percent premium being placed on the erection cost of the truss relative to the girder options. Additionally, roadway fill costs were calculated due to the reduced structure depth of the truss but substructure costs were assumed to be the same for each option. Finally, life cycle costs due to painting were accounted for in the preliminary cost estimate. Life cycle costs of annual maintenance, inspections, deck overlays and deck replacement were assumed to be the same for each option. Taking this data into account, the plate girder option was slightly less expensive than the truss option.

During this preliminary study, the following advantages and disadvantages for each option were noted:

Advantages for the Plate Girder option:

- Steel elements are below the deck and shielded from salt spray
- Fewer erection pieces
- No fracture critical members
- Possibly reduced long term maintenance and inspection costs

Advantages for the Truss option:

- Cantilever construction would eliminate temporary piers in the river
- Smaller cranes required for lighter pieces
- Lower profile resulting in less fill at the Nebraska levee
- Shipping would not require barging

Ultimately after considering the advantages of each system, a haunched girder and substringer system was selected over a steel truss alternative after being deemed more economical than a traditional multi-girder system.

Fabrication

Structural steel for the main river unit of the US 34 Missouri River Bridge was fabricated by Veritas Steel, formerly PDM Bridge, LLC. Fabrication was performed by their Palatka, Florida facility primarily due to the size of the finished girders, which required ready barge access for transport to the project site.

With the five lines of primary steel girders, the main girders were haunched to a maximum web depth of 24 feet over the piers. Field sections for these deep girders ranged up to 135 feet long with weights up to 150 tons. With relatively small flanges and thin web plates, handling the girders in the shop as well as during shipping was a challenge. Particularly during shop fabrication, girder segments had to be flipped and handled multiple times to allow access for welds and the addition of transverse and longitudinal stiffeners. Although crane capacity in the fabrication plant was not an issue, the girder fabrication was planned by the fabricator to minimize the amount of handling required for each girder segment.

One unique aspect of the girder fabrication utilized at the Palatka, Florida plant was the use of laser scanning equipment during lay down of girders to fabricate field splice plates. Ends of girder segments were drilled for field splice bolts during fabrication. Then, at girder lay down, adjacent girder segments were first fit together in a no-load position to achieve the correct gap at field splices. Then the adjoining girder segments were laser scanned to record the position of the bolt holes as shown in Figure 3. The data was fed into computer numerically controlled (CNC) equipment to drill field splice plates for the girder webs, flanges and longitudinal stiffeners. Once the splice plates were drilled, they were fit to the girders and all bolts were inserted to assure proper fit. The girder pieces were then match marked and disassembled.

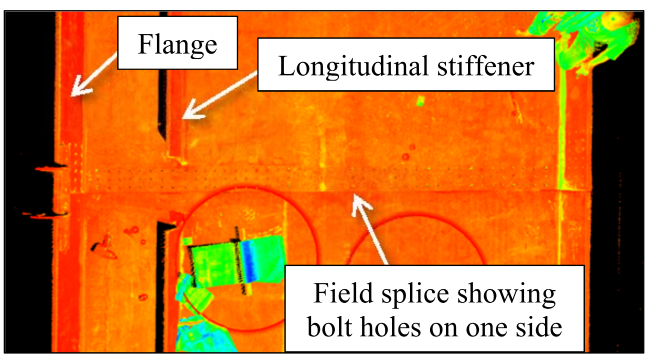

Figure 3: Laser Scan of Field Splice

At shop assembly, three field segments each for two lines of girders were blocked in a vertical position and fit up. With holes in cross frame stiffeners previously drilled during shop fabrication of girders, laser scanning and CNC equipment was again used to locate and drill holes for cross frame connection plates. Likewise, a similar procedure was used for fabricating connection plates of lateral bracing members.

The use of laser scanning equipment to interface with CNC equipment has been used by the Palatka plant for about a year and a half. Though the procedure is fairly new to the steel fabrication industry, it has been used successfully on a number of projects and other Veritas Steel plants are now beginning to use this new technology. The process provides very accurate fabrication control in the shop, streamlines shop assembly and helps eliminate fit-up problems during girder erection.

Shipping

As previously noted, Veritas Steel primarily chose to fabricate the US 34 girders at their Palatka facility due to the access the facility provided for barge shipment of the finished girders to the construction site. Due to the shipping weight of negative moment segments of the girders and with web depths up to 24 feet deep, shipment by truck was not feasible. Since shipment of the girders in an upright orientation was preferred to minimize handling stresses to shop welds, substantial special bracing and dunnage was required to support the upright girders during barge shipment. Also, the configuration of the haunched girders required the use of deck barges in lieu of hopper barges. As a result, the height restrictions of 40 feet under bridges for the St. Johns River were critical when considering the total height of the barges, dunnage and fabricated girders. Once the barges cleared the St. Johns River, the barges transited down the east coast of Florida along the Intracoastal Waterway, around the Florida Keys into the Gulf of Mexico, and finally up the Mississippi and Missouri rivers to the bridge site, which was located approximately fifteen miles south of Omaha, Nebraska.

The changing conditions on the Missouri and Mississippi rivers provided a challenge for barge shipment in 2012. Although 2011 brought widespread flooding on the lower Missouri and lower Mississippi rivers, 2012 was drastically different. Drought in 2012 brought low river levels that threatened normal barge traffic. This presented a considerable challenge to the delivery of the bridge girders, which was scheduled for late fall 2012 to coincide with the originally scheduled beginning of steel erection in winter 2013. As the shipping company was completing its transit of three barges on the Missouri River above St. Louis, there was concern that the low water levels would preclude a return of the barges past St. Louis before the end of the seasonal shipping season.

Maritime law stipulates that the cargo remains in the possession of the shipping company until all payment is received. Fearing that they would not be able to transit back down the river past St. Louis due to the low river levels, the shipping company threatened to prevent off-loading of the girders at the bridge site. The first barge was eventually off-loaded and completed its return trip down river. Ultimately the other two barges were off-loaded, but they had to be moored about 15 miles south of the project site for the winter due to low water levels. As a result, the shipping company sued Veritas Steel for the loss of use of the barges and while the issue was in litigation, the Federal Court in Iowa instructed U.S. Marshalls to "arrest" two of the girder segments pending receipt of payment for the idled barges.

The original flooding of 2011 ultimately caused a substantial delay to the project. High water levels early in the project delayed the mobilization of the bridge contractor and also caused delays to the grading contracts under other projects that would have constructed the roadway approaches, and more importantly, the earth berms for the bridge abutments on both sides of the river. The project also had environmental restrictions governing when the bridge contractor could perform clearing and grubbing operations (due to the proximity to bald eagle nests) and restrictions on when work could be performed in the river (due to the spawning season for an endangered Missouri River fish, the pallid sturgeon). With construction of the bridge substructures behind schedule, the start of girder erection was delayed until late summer 2013. While this would have seemed to work in the contractor's favor since litigation was still pending with the girder shipper, the litigation was still not resolved once girder erection started.

The girders that had been "arrested" were key segments to the orderly erection of the main river unit. To keep the erection on track, at the request of Jensen Construction, the Federal Court allowed the two critical girder segments under arrest to be exchanged for two other segments that were not currently on the critical path for girder erection. Although this swap allowed Jensen Construction to proceed with most of the erection, in the end the shipping company and Veritas Steel still could not come to terms regarding the remaining balance required to end the litigation. Faced with potential additional time delays in the Federal Court system due to the impending shutdown of the Federal Government in October 2013, Jensen Construction decided to contribute the remaining balance needed to settle the dispute. With the arrested girders released by the Federal Courts, erection continued during the fall of 2013 and the final girder segments were erected during the last week of October 2013.

Construction

The bridge girders were delivered to the construction site in late fall 2012, and the majority of the girder segments were stored and braced upright on dunnage on the Iowa side of the river. The haunched girder segments, however, were stored on custom-built pile-supported racks within the channel of the Missouri River as shown in Figure 4. These racks were configured to accommodate fluctuations in the river level and also to allow easier loading onto work barges for the short transit to the bridge during girder erection.

Figure 4: Storage of Haunched Steel Girder Pier Segments on Custom Built Racks in River

With the difficulty of river construction and thus the added time required to construct support piers in the Missouri River for the steel girder river unit, erection of the US 34 bridge superstructure first started with erection of a single unit of prestressed concrete beam approach spans on the Nebraska approach and two units of prestressed concrete beam approach spans on the Iowa approach. Prior to starting erection of the main steel river unit from Pier 4 to Pier 7 in late summer 2013, Jensen

Construction again collaborated with Veritas Steel to confirm that as-built site conditions would provide for an uneventful erection of the steel girders.

The electronic model that was used by Veritas Steel for girder fabrication and fit-up in the shop also provided for confirmation of field conditions prior to erection. Jensen Construction supplied surveyed bearing pedestal elevations and anchor bolt locations for the steel girder unit to Veritas Steel. Veritas, in turn, fed that field data into their 3-dimensional model for the steel girder unit and was able to provide feedback as to whether the pedestal elevations and anchor bolt locations matched the plan locations. Thus Veritas Steel was able to identify any potential hindrance to the erection prior to erection commencing. This check and balance process allowed for any necessary correction of deficiencies in the field prior to erection.

Jensen Construction built a scaled model of the steel girder unit within their offices in order to plan their erection sequence. Steel girder erection utilized falsework bents as shown in Figure 5 to support the anchor spans of the three-span river unit during erection. The falsework bents were supported on steel grillages that were, in-turn, placed on crane mats placed over granular fill. As positive moment sections within the anchor spans were set as paired girders between the free ends at Piers 4 and 7 and the falsework bents, the falsework towers experienced eccentric loading as the two north girder lines were set initially. The erection staging calculations also provided for a maximum probable 70 mph wind load during erection, which added to the total eccentric load demand on the towers. To resist the eccentric load, precast sections of concrete barrier rail were stacked at the base of the opposing side of the tower grillage to balance the load. Cross frames for girders were also set and bolted into place as the end segments of the three-span unit were erected.

Figure 5: Temporary Bents Utilized During Girder Erection of the Main Steel Unit

Temporary "wing" struts, as shown in Figure 6, were erected next on Piers 5 and 6 to support negative moment sections placed over these interior piers of the main river unit. The negative moment sections were also braced with cross frames as they were erected. Jensen Construction utilized two 300-ton cranes mounted on barges to perform the girder erection. With these negative moment sections weighing in at approximately 150 tons each, the contractor noted that the weights did push the limits of these cranes. The distances the cranes could boom combined with load shifting due to listing of the barges pushed the cranes near the limits of their load charts. Jensen utilized their scale model to prepare Critical Lift Plans for each girder segment that was erected to ensure that each stage of the erection was safely completed.

Figure 6: Temporary "Wing" Struts for Interior Pier Steel Section Support During Erection

Following erection of the pier segments, drop-in segments and cross frames were placed between the falsework towers and the negative moment segments erected over Piers 5 and 6 to complete the anchor spans. With girder segments in place for anchor spans on each side of the main river channel, erection of the primary girders concluded by erecting the positive moment sections and cross frames over the main river channel as shown in Figure 7. The total duration for erection was approximately three months.

Figure 7: Erection of Drop-In Steel Segments at Main Span

Following erection of the main support girders and cross frames, erection work in late fall 2013/winter 2014 will continue with installation of lower lateral wind bracing, erection of inspection catwalks, and installation of substringer beams. The balance of work to complete the US 34 Missouri River Bridge will include completion of bridge decking and barrier curbs during 2014.

Final Design

For all bridge designs, the design engineer is faced with the decision of what level of analysis is appropriate for girder design. Values of girder maximum moments and shears are dependent on a complex behavior of load transfer and geometry in three dimensions. For this project, a 3D Finite Element Model (FEM) was developed for the analysis and compared to a preliminary line girder analysis utilizing the approximate live load distribution factor equations as specified in the AASHTO LRFD (LRFD) specifications.

The LRFD specifications state that the approximate live load distribution methods covered in Section 4.6.2.2 apply to straight girder bridges, horizontally curved concrete bridges and horizontally curved steel girder bridges complying with additional specified provisions. Based on these criteria, the US 34 bridge analysis could have utilized the approximate live load distribution factors. However, LRFD further restricts the use of the approximate equations for concrete deck on steel beam bridges in Tables 4.6.2.2.2b-1 and 4.6.2.2.2d-1 for moment and Tables 4.6.2.2.3a-1 and 4.6.2.2.3b-1 for shear. According to these tables, the criteria shown in Table 1 below must be satisfied to use the approximate equations for analysis.

	AASHTO LRFD Approximate Equation Range of Applicability	**Criteria Satisfied?**
1	3.5ft $\leq$ Girder Spacing, S $\leq$ 16.0ft	NO
2	4.5in $\leq$ Depth of Slab, t_s $\leq$ 12.0in	YES
3	20ft $\leq$ Span of beam, L $\leq$ 240ft	NO
4	Numer of beams, $N_b \geq 4$	YES
5	10,000 $\leq$ Longitudinal Stiffness Parameter, K_g $\leq$ 7,000,000	NO
6	-1.0ft $\leq$ Horizontal distance from exterior beam to gutterline, d_e $\leq$ 5.5ft	YES

Table 1: AASHTO LRFD Approximate Equation Ranges of Applicability

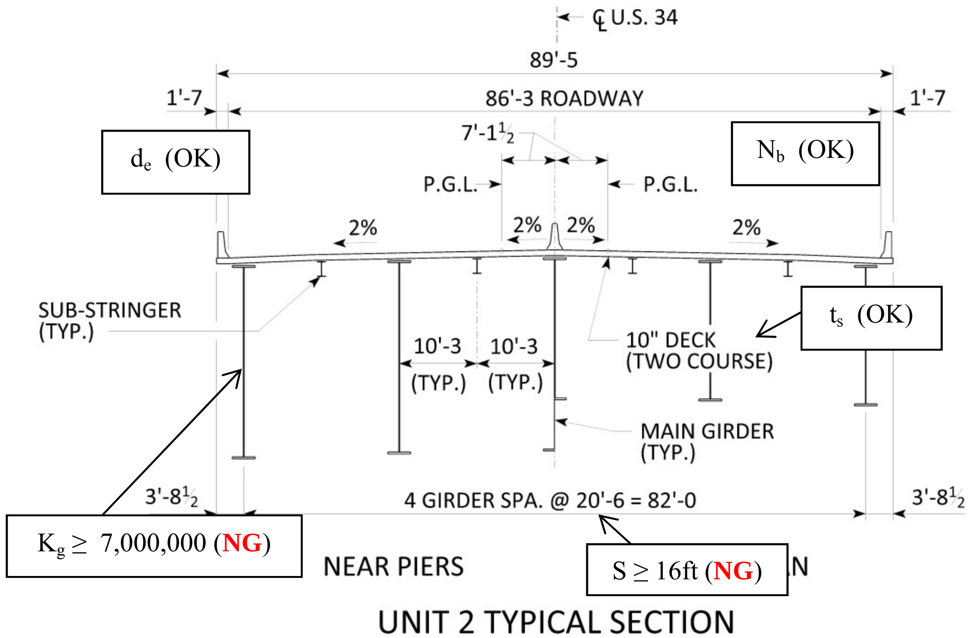

Figure 8: Typical Section Showing Violations of AASHTO LRFD Approximate Equation Criteria

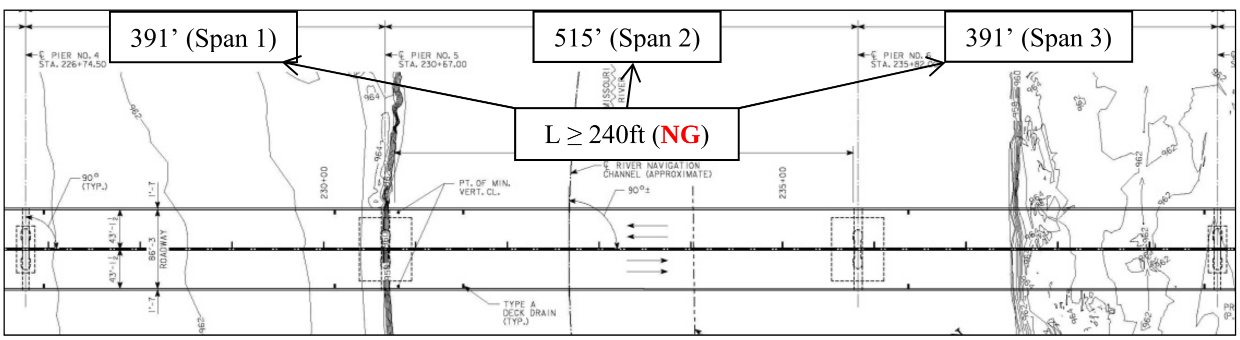

Figure 9: Plan View Showing Violations of AASHTO LRFD Approximate Equation Criteria

The range of applicability of the LRFD approximate live load distribution factors are constraints based on the original research and development of the approximate equations. Use of the specifications beyond these limits may be applicable for certain structure types. The girder substringer superstructure configuration is typically used for long span structures which would inherently exceed the specification limits for the span length, beam spacing and stiffness criteria. The US 34 Bridge exceeds several of these limits as shown in Table 1 and in Figures 8 and 9. For this reason, a 3D finite element model was created for final design analysis of the steel superstructure elements utilizing LARSA 4D software.

Until further research is established to substantiate the applicability of the LRFD approximate equations beyond the current limits, a more sophisticated analysis is required. However, the use of the equations for preliminary design and initial girder sizing is of real interest to design engineers.

To evaluate the accuracy of the LRFD approximate equations, the responses of the 3D FEM analysis were compared to the preliminary design which utilized a line girder analysis for initial plate sizing. A line girder analysis was performed for the exterior and interior girders. The exterior girder live load distribution was controlled by the rigid rotation distribution factor as specified in section 4.6.2.2d. The interior girders were controlled by the LRFD rigid rotation equation for two or more lanes loaded. The moment comparison at critical locations is shown in Table 2 and the shear comparison is shown in Table 3. As expected, in each case, the line girder results are more conservative than the 3D FEM results. Specifically, the exterior girder responses indicate the LRFD approximate equations compare closely with the more rigorous 3D FEM analysis. In addition to the US 34 project, we compared the LRFD approximate live load distribution method with another girder substringer project we previously designed. The comparison between the line girder and 3D analysis yielded very similar results to this project. Based on this limited data, the LRFD approximate live load distribution factors result in reasonable correlation to the 3D analysis for steel plate girder with substringers system. Further research would need to be performed to allow use of the LRFD approximate equations in final design of a tangent, steel girder with substringer system. However, the specifications can be reliably used for preliminary design.

Table 2: Moment Comparison – 3D FEM vs. Line Girder

Girder	Analysis Type	Max Positive Moment End Span	Max Negative Moment Interior Pier	Max Positive Moment Middle Span
		Ft-Kips	Ft-Kips	Ft-Kips
A Exterior	3D FEM (3D)	18397	-26608	19287
	Line Girder (LG)	19741	-29665	20053
	Delta (LG/3D)	*+7.3%*	*+11.5%*	*+4.0%*
B Interior	3D FEM (3D)	17237	-24595	18115
	Line Girder (LG)	21045	-34856	19781
	Delta (LG/3D)	*+22.1%*	*+41.7%*	*+9.2%*
C Interior	3D FEM (3D)	16611	-24207	17432
	Line Girder (LG)	21045	-34856	19781
	Delta (LG/3D)	*+26.7%*	*+44.0%*	*+13.5%*

Table 3: Shear Comparison – 3D FEM vs. Line Girder

Girder	Analysis Type	Max Shear End Support	Max Shear Interior Support End Span Side	Max Shear Interior Support Middle Span Side
		Kips	Kips	Kips
A Exterior	3D FEM (3D)	207	297	293
	Line Girder (LG)	220	285	297
	Delta (LG/3D)	*+6.3%*	*-4.0%*	*+1.4%*
B Interior	3D FEM (3D)	178	273	287
	Line Girder (LG)	323	416	435
	Delta (LG/3D)	*+81.5%*	*+52.4%*	*+51.6%*
C Interior	3D FEM (3D)	201	295	309
	Line Girder (LG)	323	416	435
	Delta (LG/3D)	*+60.7%*	*+41.0%*	*+40.8%*

Summary & Recommendations

The US Highway 34 Missouri River Bridge consists of 4 units totaling 3,276-feet with the main navigational unit length of 1,297-feet. The main river unit superstructure utilizes haunched steel girders with substringers and ASTM A709 50W steel. This option was chosen over a steel truss option and a traditional multi-girder system after a preliminary bridge type study was conducted. Fabrication of the steel girders was very challenging due to the size of the sections and the intricacy involved with picking, handling and shipping to the construction site. Due to the girder size, the only feasible shipping option was by barge. Furthermore, during fit-up, the fabricator utilized laser scanning technology and computer numerically controlled drilling techniques to custom fabricate each splice plate and portions of the crossframe and lateral bracing connections. Construction of this bridge was also complicated by the size and weight of the field sections. This complication was further exacerbated due to the need to erect the bridge with barge-mounted cranes. The size of steel sections pushed the limits of what a typical contractor is able to handle without the use of more specialized equipment. During final design, the 3D FEM live load results were compared to the preliminary line girder live load results for moments and shears. This serves as a direct comparison between the LRFD approximate equations for live load distribution and a more refined analysis for a tangent, steel plate girder with substringer system. The line girder results were conservative and can be used to obtain initial plate sizes that will closely match the final design. The engineer's cost estimate for the entire project, including the approach units, was $62.2 Million ($212/SF) and the low bid came in at $61.3 Million ($209/SF). There were six bidders and the range of bids was between $61.3 Million ($209/SF) and $91.4 Million ($311/SF). The cost of the structural steel on this project was approximately $20.3 Million which corresponds to a fabricated steel cost of $1.76/LB. This bridge is currently under construction and should be completed in late 2014.

Acknowledgements

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