

DESIGN OF BUCHANAN COUNTY, IOWA, BRIDGE, USING ULTRA-HIGH PERFORMANCE CONCRETE AND PI-GIRDER CROSS SECTION

Dean Bierwagen, PE, Bridges and Structures, Iowa DOT, Ames, IA

Brian Moore, PE, Wapello County Engineer, Ottumwa, IA

Brian Keierleber, PE, Buchanan County Engineer, Independence, IA

Sri Sritharan, Phd, Iowa State University, Ames, IA

Terry Wipf, Phd, P.E., Bridge Engineering Center, Iowa State University, Ames, IA

Ahmad Abu-Hawash, PE, Bridges and Structures, Iowa DOT, Ames, IA

ABSTRACT

Using Federal funding through the TES-21 Innovative Bridge Construction Program (IBRC), managed by the Federal Highway Administration (FHWA), Iowa has been developing a base of design and construction experience with ultra-high performance concrete (UHPC). With the funding provided, two bridge projects have been completed in Iowa using the UHPC material. Working with FHWA, Iowa State University and Lafarge North America, engineers at the Iowa Department of Transportation, Wapello County, Iowa and Buchanan County, Iowa have designed and constructed two highway bridges using UHPC.

The first in Wapello County was a single span 110 ft prestressed beam bridge with the beams cast using UHPC. The 110 ft UHPC beams were cast with 0.6 inch diameter pretensioned strands and without mild reinforcing steel, except to provide composite action with a cast-in-place deck. A 71 ft long test beam was also cast and tested at Iowa State University, Ames, Iowa to verify shear and flexural capacities of the bridge beams. The three 110 ft bridge beams were cast in June and July 2005. Construction of the bridge was completed in the fall of 2005 with the bridge officially opened in spring of 2006.

The second bridge was built in Buchanan County, Iowa, using an optimized pi-girder section with UHPC and was the first application of the pi-girder for a highway bridge in the United States. The girders was pretensioned longitudinally and tied together transversely with mild reinforcing steel and steel diaphragms. The design was based on conventional and finite element analysis, which was validated by prior laboratory testing of the first and second generation pi-girder at the FHWA's Turner-Fairbank Highway Research Center in McLean, Virginia near Washington, DC. The beams were fabricated in September, 2008 and construction of the bridge was completed in October 2008. The bridge was officially opened in the spring of 2009.

In a continuation of the work on UHPC with funding from a FHWA Highways for Life Tech Partnership Grant, a third project is currently underway. Coreslab Structures of Omaha, Nebraska, Wapello County, IA; Iowa State University; Lafarge North America, FHWA and the Iowa Department of Transportation are teaming up on this third bridge

project. The project will use precast deck panels cast with UHPC in a waffle configuration. Phase I testing of the waffle slab is about complete. Once approved by the FHWA, phase II will be construction of a simple span 60 ft prestressed bridge in Wapello County, Iowa, using the approved UHPC waffle slab configuration.

This article gives an overview of the UHPC work that has been done by Iowa and the experience gained from laboratory testing, casting, construction, field load testing and monitoring of these two bridges and the current status of the third UHPC project with the waffle panels.

Keywords: Ultra-High Performance Concrete, Ductal[®] Concrete, Optimized Cross-Section, Pi-Girder, Prestressed Girder, Precast Waffle Panels, Steel Fiber, Finite Element Modeling, Analytical Models

INTRODUCTION

Developed in France during the 1990s, ultra-high performance concrete (UHPC) has seen limited use in North America. UHPC consists of fine sand, cement, and silica fume in a dense, low water-cement ratio (0.15) mix. Compressive strengths of 18,000 psi to 30,000 psi can be achieved for UHPC, depending on the mixing and curing process. The material has a low permeability and high durability. To improve ductility, steel or polyvinyl alcohol (PVA) fibers (approximately 2% by volume) are added, which essentially eliminates the need for using mild steel reinforcement. For all projects discussed in this paper, the patented mix Ductal[®] developed by Lafarge North America was used with the steel fibers.

This paper summarizes Iowa's experience with UHPC by covering:

1. Wapello County Bridge Project (Modified Iowa Bulb Tee)
2. Buchanan County Bridge Project (Pi Girder)
3. Wapello County Bridge Project (Waffle Slab)

WAPELLO COUNTY BRIDGE PROJECT (MODIFIED IOWA BULB TEE)

Overview

In 2003, Wapello County and the Iowa Department of Transportation (IDOT) were granted funding through the TEA-21 Innovative Bridge Construction Program (IBRC), for a project utilizing ultra-high performance concrete (UHPC). UHPC was used in three prestressed concrete beams in a bridge replacement project in southern Wapello County.

The modified bulb tee beams were prestressed using 0.6-inch diameter low relaxation strands. No mild reinforcing steel except to provide composite action between the beams and a cast-in-place deck were used. To verify shear and flexural capacity of the bridge beams, 10-inch and 12-inch shear beams, and a 71 ft. long test beam were cast. Testing was completed by Iowa State University (ISU) and the Bridge Engineering Center (BEC) in Ames, Iowa, in the Fall of 2004.

Casting of the 110 ft production beams was completed in June and July, 2005. Construction of the bridge began in August, with the 110 ft beams arriving at the job site in September, 2005. Immediately following completion construction, the bridge officially opened to traffic in the spring of 2006.

Project Development

Because of the uniqueness of UHPC and the special requirements for designing, mixing, casting, and curing, this first project was organized into stages as listed below to facilitate all parties involved in the project to gain sufficient experience and confidence. Listed below are various activities and stages and their completion dates.

1. Ultra-High Performance Concrete Design Seminar (Completed 8-12-03).
2. Test batch at Iowa Department of Transportation Materials Laboratory in Ames (Completed 12-11-03).
3. Review of precasting plants (Completed 12-11-03).
4. Additional test batch at Materials Laboratory in Ames (Completed 1-26-04).
5. Test batch at precasting plants (Completed 4-12-04).
6. Casting of shear beam specimens (Completed 1-24-05).
7. Casting of 71 ft. test beam (Completed 2-23-05).
8. Flexure testing of 71 ft. test beam (Completed 5-12-05).
9. Shear testing of 71 ft. test beams (Completed 6-9-05).
10. Public letting for construction of bridge (Completed 6-20-05).
11. Casting of three 110 ft. production beams (Completed 7-16-05).
12. Bridge construction begins (Completed 8-17-05).
13. Concrete bridge deck placed (Completed 11-8-05).
14. Two year evaluation of finished bridge after construction (Completed summer 2008).

Design Seminar

On August 12, 2003, the BEC and Iowa DOT organized a seminar on ultra-high performance concrete to provide information to people that would be involved in the project. The seminar was sponsored by the FHWA and attended by participants from the FHWA, DOT, Wapello County, precast industry and ISU.

Test Batch at Materials Laboratory Ames, Iowa

Two test batches were done in the DOT Materials Laboratory in Ames, Iowa. On December 11th 2003 and January 26th, 2004. Personnel from the precasting industry, Iowa DOT, ISU and CTRE attended. Lafarge provided the test mix and also demonstrated the mixing procedure (See Table 1 for mix proportions). For the demonstration, a 1958 Lancaster mixer with a two cubic foot capacity was used to produce a one cubic foot batch of UHPC (See Figure 1). Three inch by six inch test cylinders were cast in the first and second test mix and 2 inch cubes were cast in the second mix. Specimens were cast on a vibrating table using a small plastic tremie tube.

Curing of the specimens from the first test was improperly completed and compressive test results were lower than expected with an average of 16,990 psi. Expected values were 30,000 psi. These lower compressive strengths were due to the lack of experience with the initial set time, curing process, and the difficulty in preparing the ends of the specimens for compressive testing. Based on discussion with FHWA and Lafarge proper preparation of the test cylinder ends is essential for reliable compressive strength test. Figure 2 shows the broken test cylinders from the first tests showing non-uniform compressive failure.

Table 1. Test Mix Proportions

Description	Quantity
Ductal Mix	137 lbs
Water	8.03 lbs
3000NS (Super Plasticizer)	850 g
Steel Fibers	9.7 lbs

**Figure 1. Mixing of UHPC in the Materials Laboratory of Iowa DOT**

Therefore, a second test was completed to try and improve the test results. For this mix, three inch diameter by six inch tall test cylinders were again cast along with two-inch cubes. Bronze mortar forms were used for the casting of the two inch cubes. The cubes provided a test specimen with plane sides that did not require end preparation.

These specimens were cured in sealed steel containers in ovens at 195 degrees F with 95% humidity for 40 hours (See Table 2 and Table 4) and in water (See Table 3). Compressive strengths of the cylinders improved, but were still lower than expected for the cylinders. Again difficulty in ensuring horizontal plane surfaces for the ends of the test cylinders for uniform compression loading was believed to be the main cause of the lower strength values. Testing values for the 2 inch cubes were closer to the expected strength of 30,000 psi.

Table 2 (95% Humidity)

2 inch cubes	Compressive Strength (psi)
1	29,930
2	27,540
3	30,610

Table 3 (Water Cured)

2 inch cubes	Compressive Strength (psi)
1	31,210
2	30,750
3	27,640

Table 4 (95% Humidity Cured)

3 inch x 6 inch cylinders	Compressive Strength (psi)
1	23,820
2	24,570
3	22,510

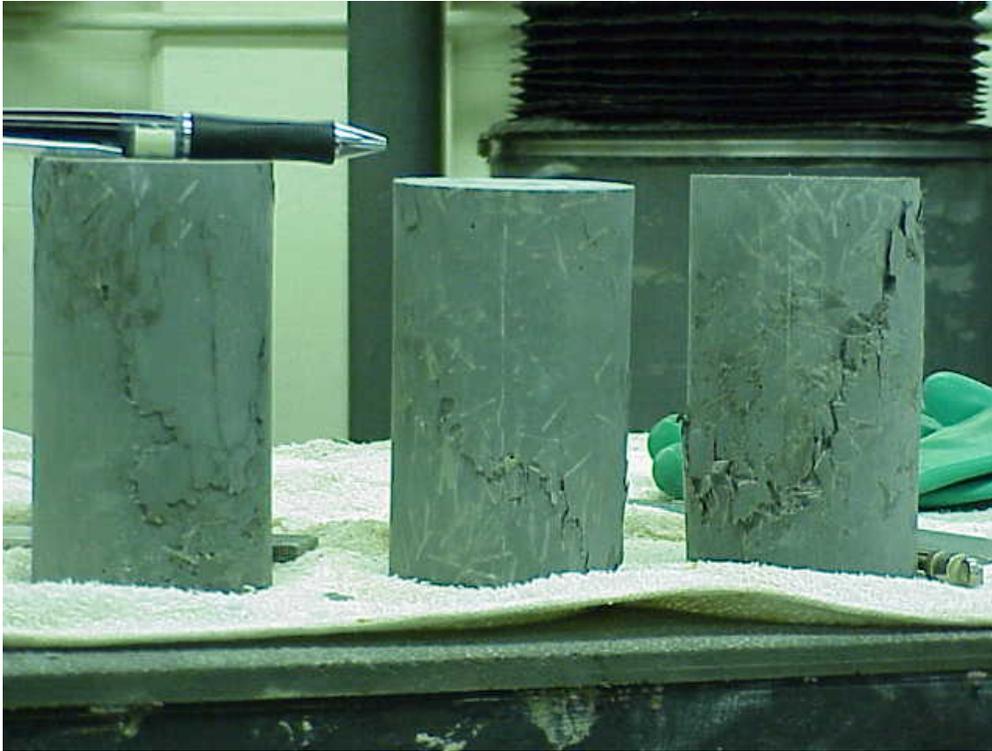


Figure 2. Broken Test Cylinders

Certification of Local Precasting Plants

Two local precasting plants expressed an interest in casting the beams for the project and were certified by Lafarge to batch the UHPC. The UHPC was batched successfully at each plant. However, there were concerns expressed by the precasters on the batching process, which are listed below:

1. The high cost for patented UHPC mix.
2. The longer time to batch the mix (possibly 15 to 30 minutes per batch) and additional cleaning time for mixers because of the use of steel fibers and fine aggregate.
3. Increased chances of damaging mixing equipment, due to the high mixing energy requirement.
4. Proper placement of UHPC in forms and the requirement to produce the entire UHPC mix before placement can be started. This requires use of redi-mix trucks to temporarily store the batches until the full amount is ready for placement.
5. Because of the large amount of cement in the mix, shrinkage values are estimated to be twice the amount of standard mixes. Modifications of forms is required to compensate for the additional shrinkage or forms need to be

- partially removed (broken) to prevent cracking of the concrete. In addition, properly timed release of the strands is also important due to the high shrinkage expected.
6. Long setting and curing time (approximately 40 hours set time and 48 hours of 195 degrees steam cure) and the lost production time in the casting beds.
 7. Lack of testing equipment required to:
 - a. evaluate the UHPC mix flow; and
 - b. prepare the three inch by six inch test cylinders for proper compressive testing.

Because of these concerns, bids that were received from the local precasters for the first bridge project were too high to be covered by the research funding and the beams were cast by Lafarge North America at their Winnipeg precast plant in Manitoba, Canada.

Test Beam Design

Wapello County, the Iowa Department of Transportation, Office of Bridges and Structures, and the Bridge Engineering Center at Iowa State University jointly designed and prepared plans for the test beam as well as the prototype bridge and production beams. The design of the beams was a challenge for the team. No design specifications for UHPC are available even today in the United States. To complete the design, guidelines were gathered from a number of sources including:

1. French guide specification for UHPC.
2. Research and design recommendations from Dr. Ulm of MIT.
3. "Design guidelines for RPC Prestressed Concrete Beams, University of new South Wales".
4. Discussions with Vic Perry of Lafarge, Chris Hill of Prestressed Services of Lexington, Kentucky and Ben Graybeal of FHWA, Turner-Fairbanks.

Based on the information gathered, the following design limits, loading, and distribution were used:

- | | |
|---|------------|
| 1. Release Compressive Strength | 14,500 psi |
| 2. Release modulus of elasticity | 5,800 psi |
| 3. Final Design Compressive Strength | 24,000 psi |
| 4. Final modulus of elasticity | 8,000 psi |
| 5. Allowable tension stress at service | 600 psi |
| 6. Allowable compression stress at service | 14400 psi |
| 7. LRFD HL-93 loading | |
| 8. Grillage analysis for distribution factors | |

The modified section was developed from the standard Iowa 45-inch bulb tee. See Figure 3 for details of standard bulb tee section. Working with Dr Ulm of MIT a revised bulb tee section was developed to save material. The section reduced the web width by two inches to 4½ inches, top flange by one inch to 2-13/16 inches and the bottom flange by two inches to 5½ inches. See Figure 4 for revised section.

Based on the span length and beam spacing for the final bridge section the test beam was cast using 49-0.6 inch strands stress to 72.6 percent of ultimate. To reduce end beam stresses five strands were draped along with de-bonding of additional straight strands in the bottom flange (See Figure 5 for final strand configuration). Once testing was successfully completed this beam was used in the final bridge project.

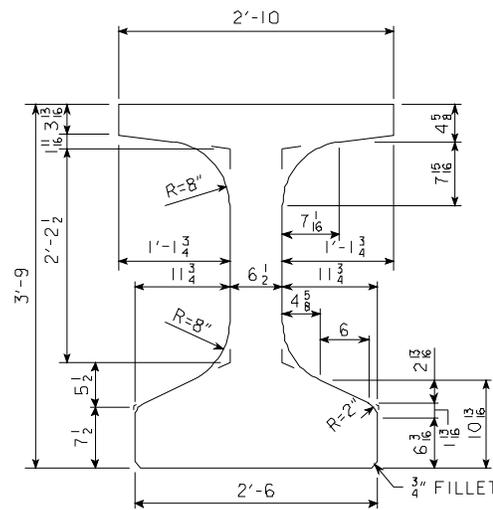


Figure 3. Iowa 45-inch Bulb Tee Section

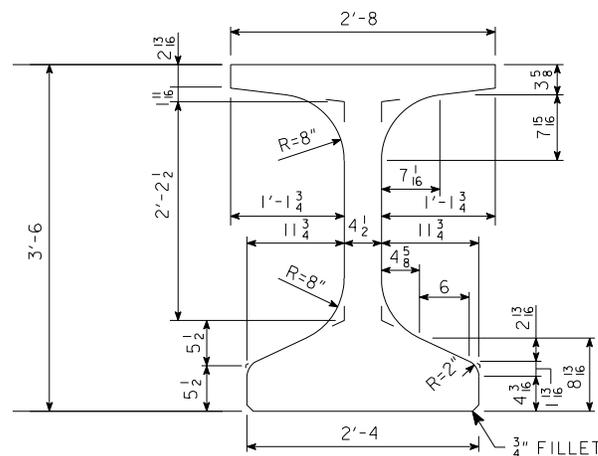


Figure 4. Modified Section for UHPC

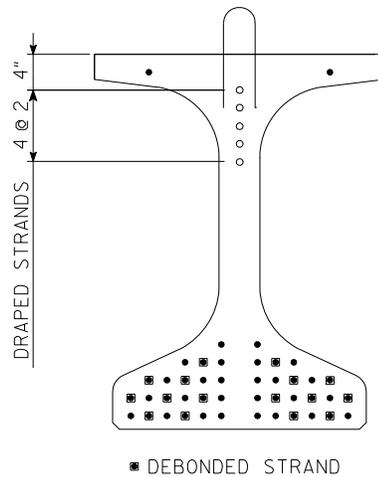


Figure 5. Strand Layout of the UHPC Girder Section

Casting

As mentioned earlier in the report, casting of the beams took place at the Lafarge precasting plant in Winnipeg, Manitoba, Canada. Individual batches were temporarily stored in a redi-mix truck and placement of the mix was started once all the UHPC had been mixed. Placement by the redi-mix truck started at one end of the form and the concrete mix was allowed to flow through the form. As the form filled up at the starting end the redi-mix truck moved along the beam until the placement was complete. No internal or external vibration was used during the casting operation. See Figure 6 and 7 for pictures showing the casting and completed 110 ft beam in the casting yard, respectively.

Research had shown that the improved bond strength of the UHPC could reduce significantly the transfer length of the strands and could cause a concentration of release forces and cracking at the interface between the bottom flange and web. As mentioned earlier, both debonding and draping of the strands were provided to reduce these forces. Close inspection of the beam after release of the strands showed no visible cracks at the interface area even though no mild reinforcing was provided in these end transfer areas.



Figure 6. Casting of 110 ft. UHPC beam used on Wapello County Bridge



Figure 7 UHPC beams prior to shipping to bridge site in Wapello County

Beam Tests (Flexure, Shear and Flexure-Shear)

Flexure, shear, and flexure-shear tests were successfully completed by the Bridge Engineering Center at Iowa State University on the 71 ft-long prestressed bulb tee UHPC beam (Degen, 2006).

The flexure test was limited to the initial concrete cracking load to allow for ultimate shear testing of an undamaged beam section. There was concern that flexure testing to failure might adversely affect the ultimate shear test and flexure-shear test to be done at the beam ends. The flexure test was performed on May 12, 2005 in the structures lab at Town Engineering Building, ISU, Ames, Iowa. Four jacks were placed symmetrically at the midspan spaced 2.6 ft and 4.5 ft from the centerline of the span (See Figure 8). Estimated cracking load for the beam was between 240 kips and 280 kips based on the loss estimates. Actual cracking was noted at 64 kips per jack or 256 kips total. Maximum load that was applied to the beam was 264 kips which resulted in 3 ¼ inches of deflection at the mid span.

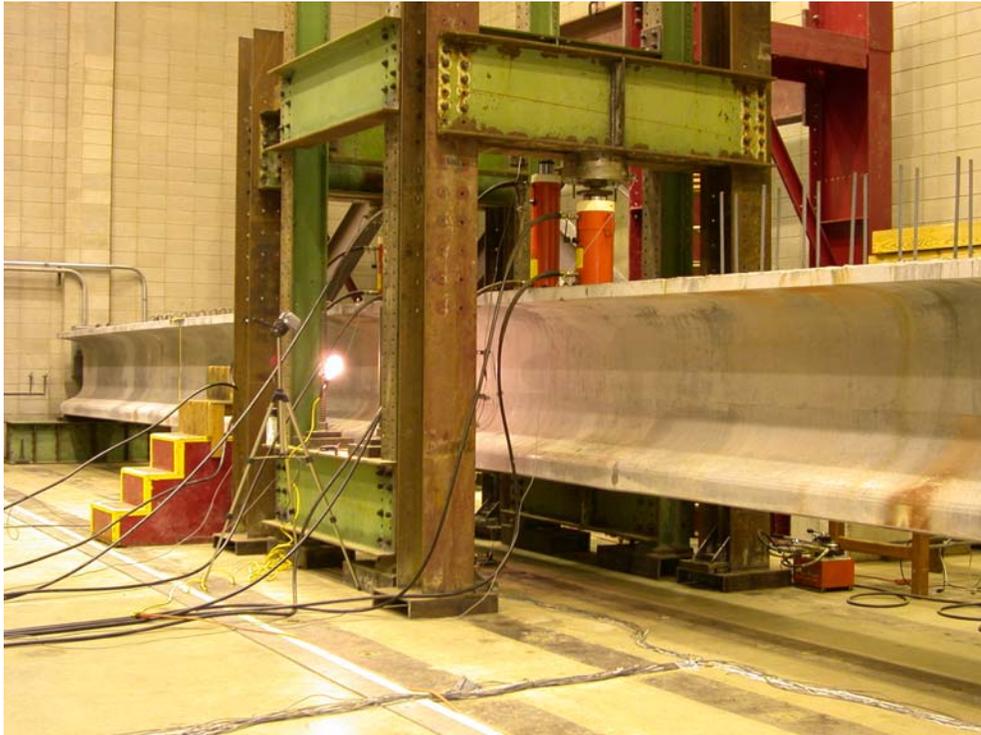


Figure 8. Flexure Test of the 71 ft-long UHPC beam at ISU

The ultimate shear test was performed on June 9th, 2005. Shear cracking developed at a total load of 370 kips (315 kips at the beam test end). Total load applied at failure was 594 kips (501 kips at beam test end). See Figure 9 and 10 for test setup and failed beam end). In addition to the shear cracking, the beam end also split down the centerline of the beam section. The reason for this split was discussed but the cause of the failure was not determined.

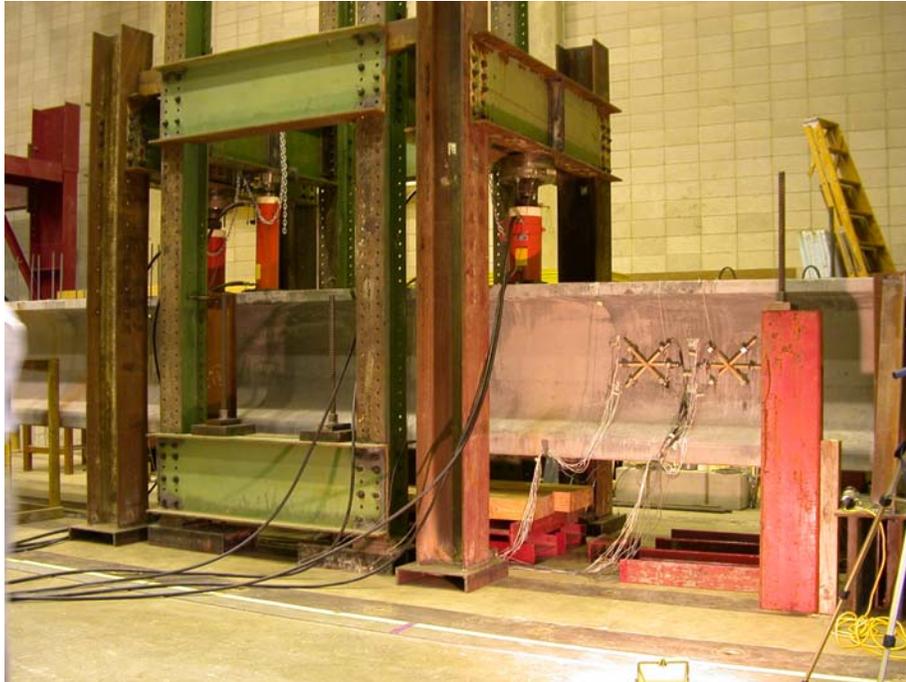


Figure 9. Shear Test Setup.

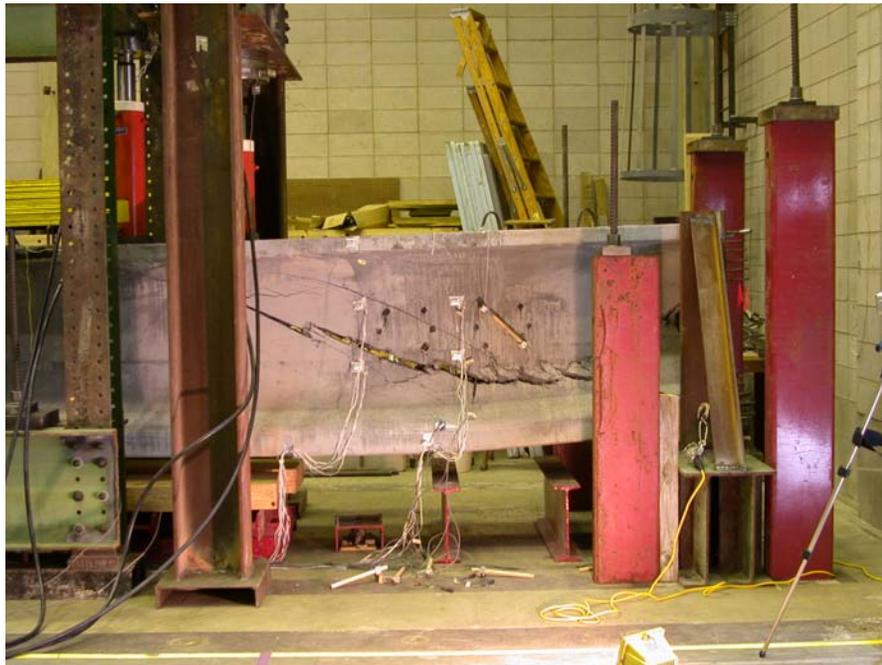


Figure 10. Failed End Section.

On August 5th, 2005, the flexure-shear test was performed. The test was on a 57 ft span with the first load point 17 ft 6 in from a support point. Four load points were used at spacing of 3 ft 0 in, 1 ft 10 in, and 5 ft

4 in. A total load of 367 kips was applied before cracking was noted. The total load applied was 658 kips with a maximum deflection of 8.5 inches. The beam was unloaded at this point even though more load could have been applied (Degen 2006).

Bridge Construction

Once the beams were cast, construction of the bridge proceeded similar to a typical prestressed beam bridge that would be constructed in Iowa. The bridge replacement project was located south of Ottumwa, Iowa (see Figures 11 and 12). It was a 110 foot simple span bridge with a three UHPC beams used in the cross section as shown in Figure 13. The cast-in-place integral abutments and an 8 inch cast-in-place deck were used. Beam spacing was 9 foot 7 inches with 4 foot 0 inch overhangs. Load testing was provided by the Bridge Engineering Center at ISU after the bridge was constructed and additional load tests were done two years later (Wipf, 2008). See Figure 14 for picture of completed bridge.

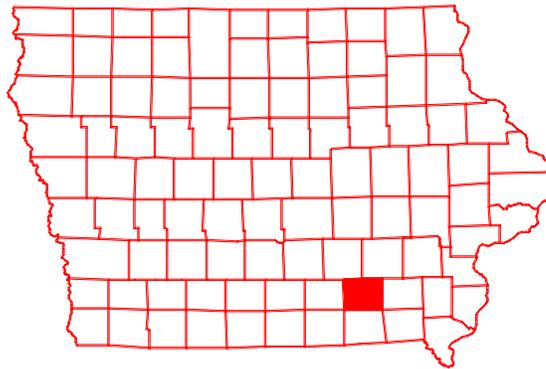


Figure 11. Project Location (Wapello County)

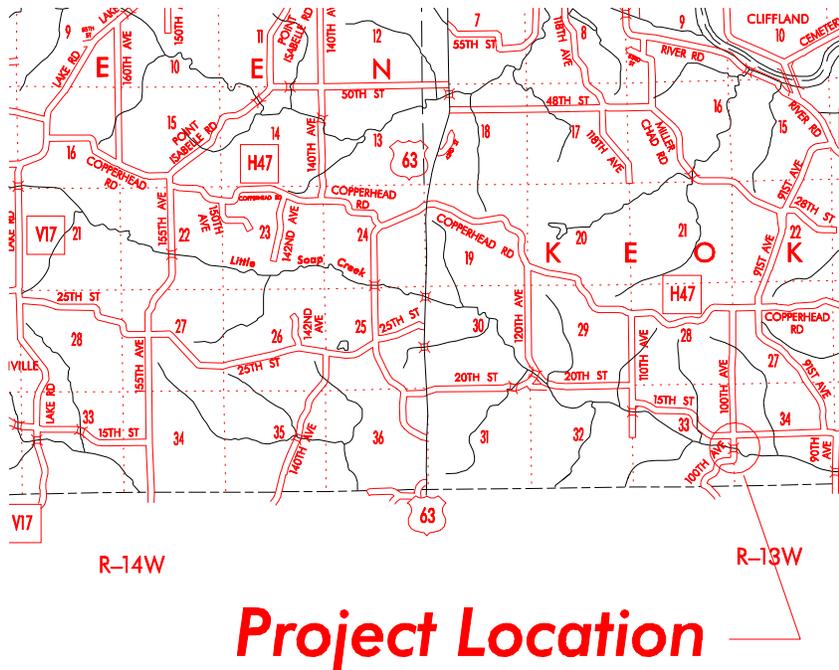


Figure 12. Project Location

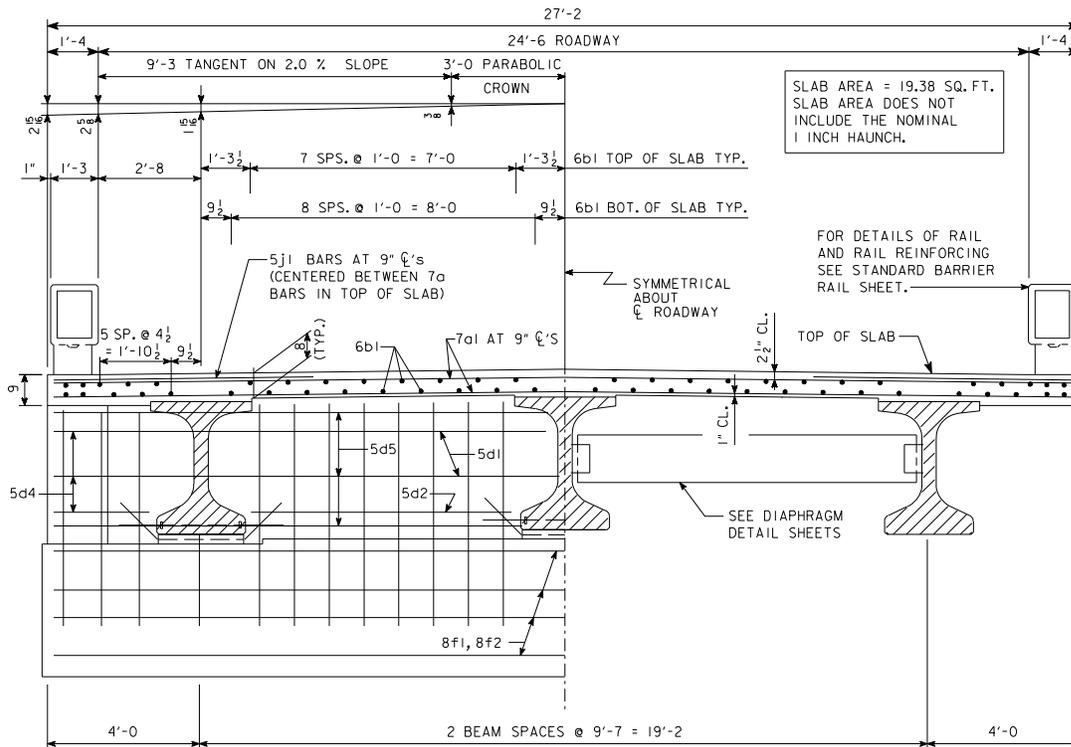


Figure 13. Proposed Bridge Cross Section



Figure 14. Completed Wapello County Bridge

BUCHANAN COUNTY BRIDGE PROJECT DESCRIPTION

After the successful project in Wapello County, Iowa was given an opportunity to build on the experience with a second UHPC bridge project. This bridge was built in Buchanan County, Iowa, using an optimized pi-girder section cast with UHPC and was the first application of the pi-girder for a highway bridge in the United States. The girders were pretensioned longitudinally and tied together transversely with mild reinforcing steel and steel diaphragms. The design was based on conventional and finite element analysis, which was validated by laboratory testing of the first and second generation pi-girder at the FHWA's Turner-Fairbank Highway Research Center in McLean, Virginia near Washington, DC. The production beams were fabricated in September, 2008 and construction of the bridge was completed in October 2008. The bridge was officially opened in the spring of 2009.

Design

For the design, the team again took advantage of the design work that was done for the bridge project in Wapello County, along with the testing by the Bridge Engineering Center and Turner-Fairbank Highway Research Center. Research reports and guide specifications listed below were also used, as well as discussions with Ben Graybeal (FHWA) and Vic Perry (Lafarge):

1. Research and design recommendations from Dr. Ulm of MIT (Ulm 2004)
2. Design Guidelines for RPC Prestressed Concrete Beams, University of New South Wales (Gowripalan and Gilbert 2000)

3. Structural Behavior of Ultra-High Performance Concrete Prestressed I-Girders, Publication No. FHWA-HRT-06-115 (Graybeal 2006a)
4. Material Property Characterization of Ultra-High Performance Concrete, Publication No. FHWA-HRT-06-103 (Graybeal 2006b)

Material properties and design stresses of the Ductal[®] mix were based on experience with the Wapello County project, FHWA testing, and recommendations by FHWA and Lafarge. Values are shown below:

Modulus of elasticity at release	5,800 ksi
Modulus of elasticity final	7,800 ksi
Design compressive strength at release	14,500 psi
Design compressive strength final*	21,500 psi
Tensile strength	1,200 psi
Allowable compressive release stresses 0.6 (12,500 psi)	7,500 psi
Allowable compressive stress at service 0.6 (21,500 psi)	12,900 psi
Allowable tensile stress at service 0.7 (1200 psi)	840 psi

(* heat curing is required to reach the final compressive strength)

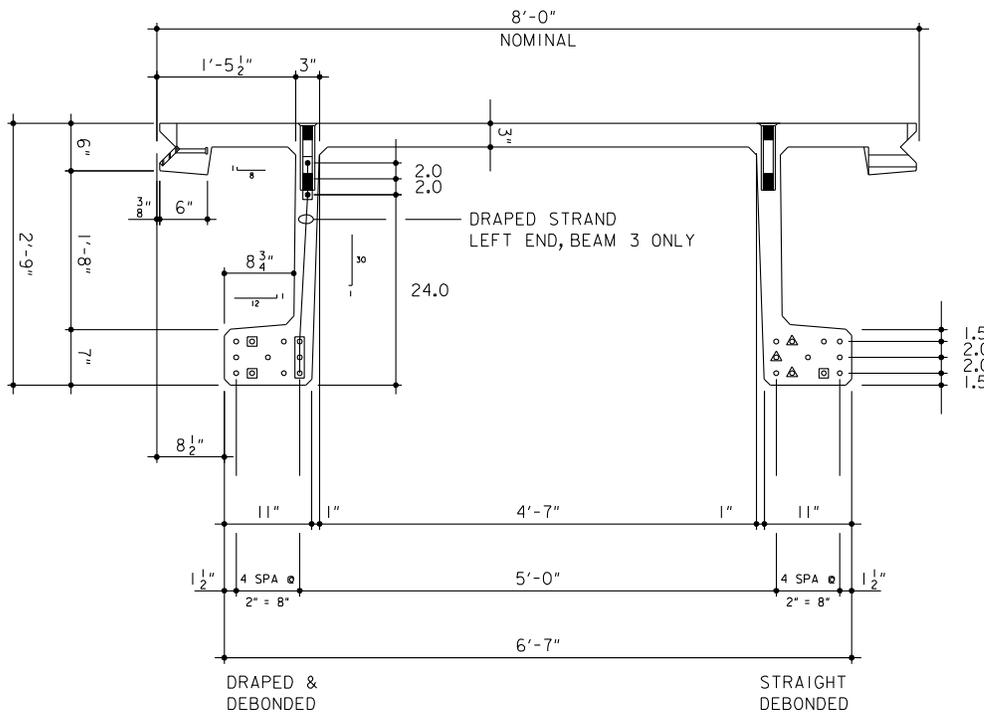


Figure 15. Initial (first generation) Pi-girder

Beam Design

The design used the first generation pi-girder, Figure 15, developed by the FHWA's Turner-Fairbank Highway Research Center and MIT as a starting section (Graybeal, B.A. 2009). The section was developed to optimize the UHPC mix by minimizing the cross section and taking advantage of the UHPC properties in the bridge deck. Testing of the section by Turner-Fairbank had validated the FEM analysis and first generation geometry for flexural and shear capacity in the longitudinal direction. The testing also confirmed that the stress in the transverse direction of the deck were unacceptable for service loading and a low transverse live load distribution between adjacent pi-girders would require stiffening. See Figure 16 for a testing photo. An attempt was made to strengthen the section while still using the first generation pi-girder forms. Because of the high cost to modify the forms, FHWA offered to purchase new forms using a revised (second generation) pi-girder. Working with FHWA a revised section was developed. See figure 17 for details of the revised section.

Along with the purchase of the new forms, FHWA also purchased two beams for testing. The three production bridge beams for the project were also purchased at the same time helping to reduce the setup and casting cost of all beams.



**Figure 16. Transverse deck test of first generation pi-girder at Turner Fairbank Laboratory
(Photo courtesy of FHWA)**

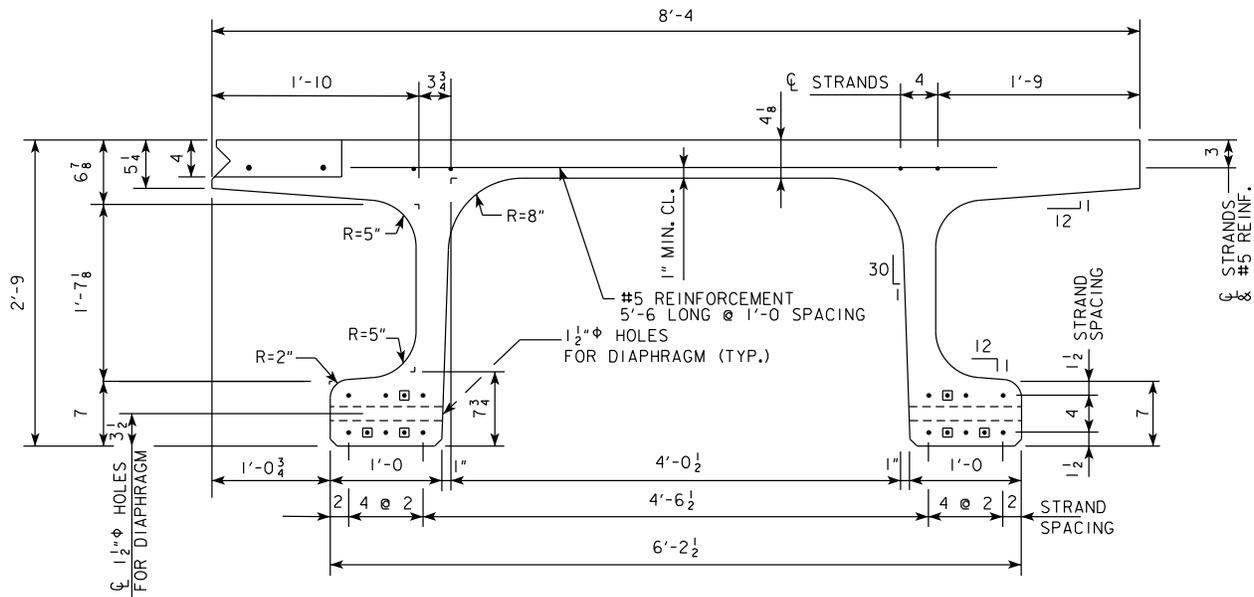


Figure 17. Modified (second generation) pi-girder

Summary of the modifications made to the pi-girder are as follows:

1. Five inch and eight inch radii were added at the web to deck connection to improve concrete mix flow during casting and stiffen the slab section.
2. The interior deck thickness between the webs was increased to 4 1/8 inches to meet service stresses in an uncracked condition.
3. The web spacing was reduced by four inches to provide a more balanced spacing of the webs for the three beam cross section and reduce service stresses.
4. Due to the lack of test data on the revised section, mild reinforcing steel was included in the deck (# 5 reinforcing steel at 1'-0 spacing).
5. Grouted reinforced pockets with No. 8 reinforcing tie bars were provided at 18 inch spacing for the girder connections in the slab. See Figure 18 for details.

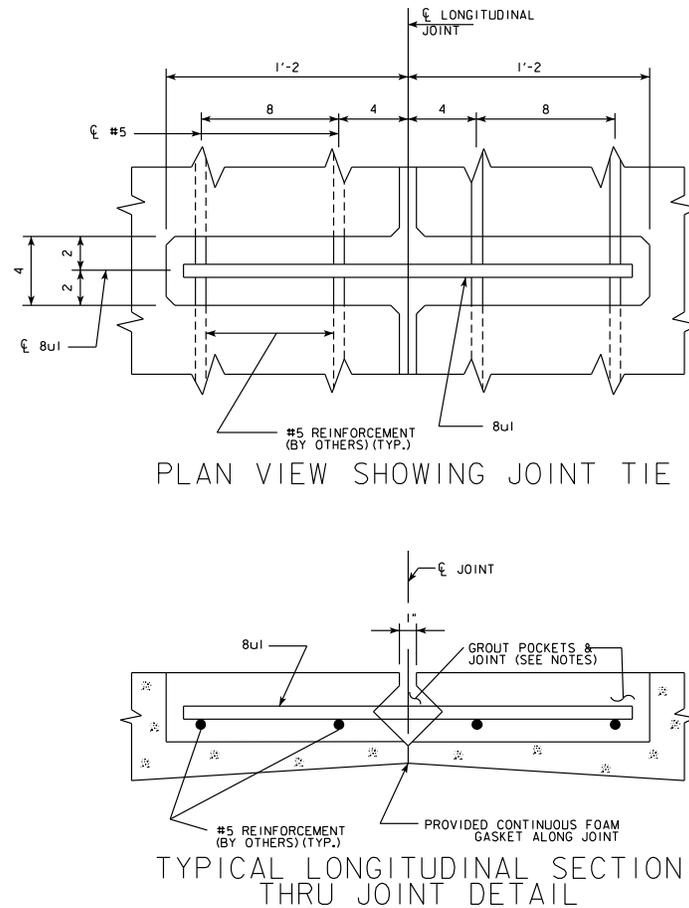


Figure 18. Slab Connection between adjacent pi-girders tested at Turner Fairbank Laboratory

Bridge Description

The replacement bridge project is located on a county road (136th Street) over the east branch of Buffalo Creek in northeast Buchanan County, Iowa (see Figures 19 and 20). The roadway width is 24 ft 9 in. wide by 115 ft. 4 in. long. The center span (the UHPC segment of the bridge) is 51 ft. 2 in. from center to center of the pier caps (Figure 21). The 50 ft. 0 in. simple span pi-girder is supported on plain neoprene bearing seats (see Figure 22 for cross section details). The beam ends are encased in cast-in-place concrete diaphragms with 3,500 psi compressive strength. End spans are cast-in-place traditional reinforced concrete slabs with integral abutments supported on steel HP10x42 piles and the pier caps are supported on steel HP10x42 piles encased in concrete as shown in Figure 23.

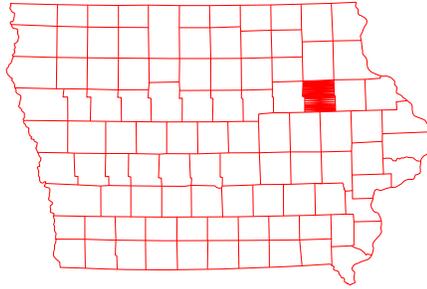


Figure 19. Location of Buchanan County in Iowa

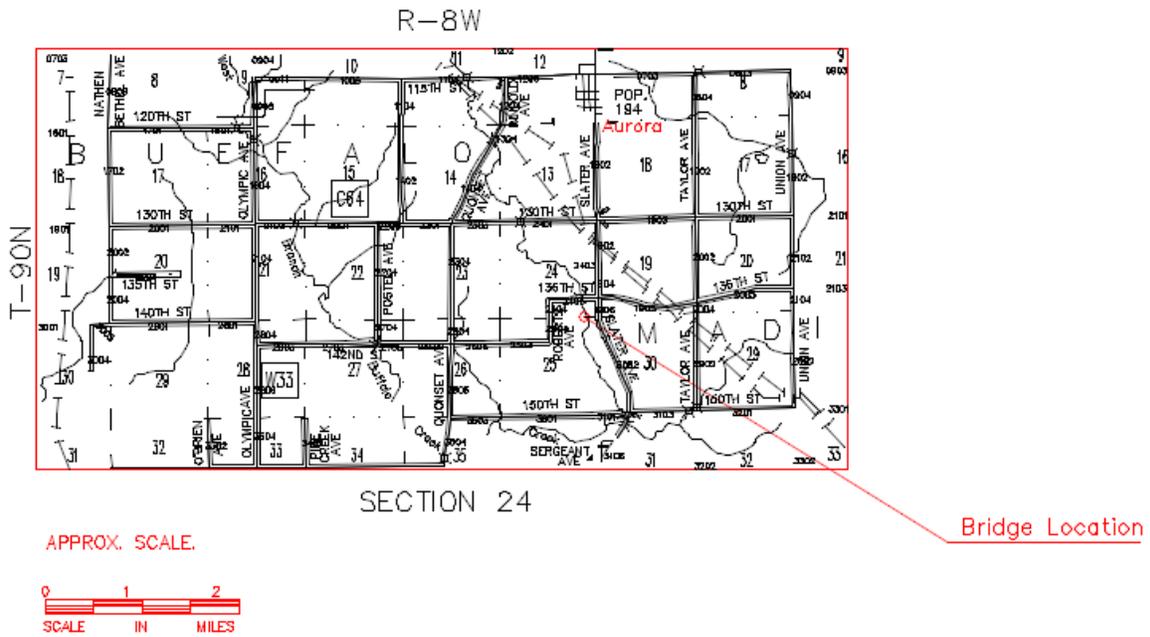


Figure 20. Bridge location in Buchanan County

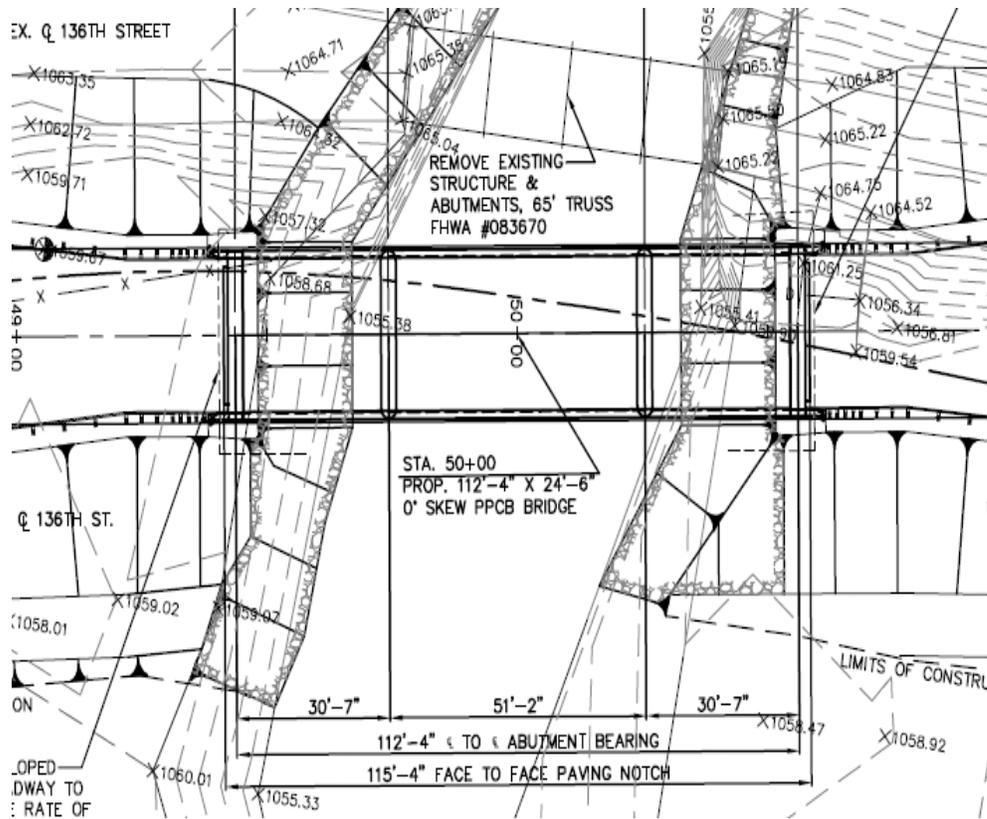


Figure 21. Situation plan of Buchanan County pi-Girder Bridge

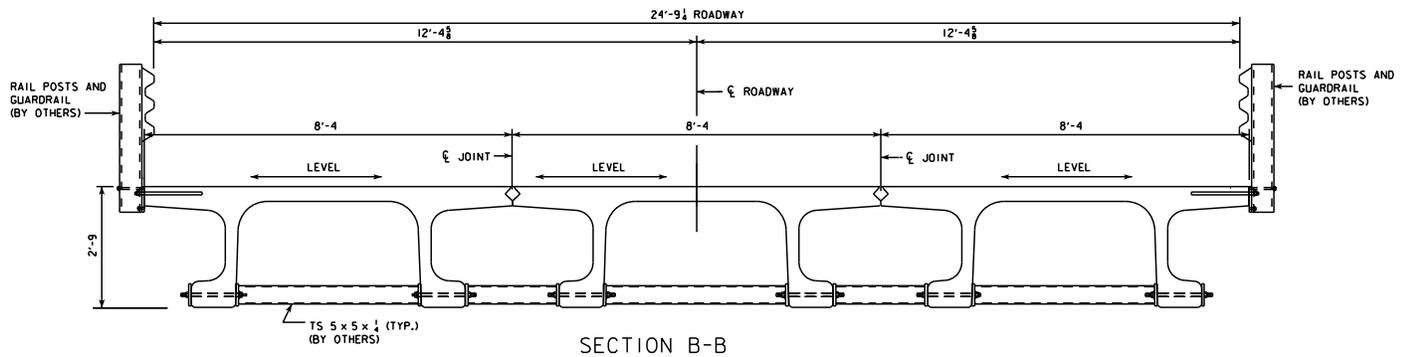


Figure 22. Proposed bridge cross section for the Buchanan County Bridge

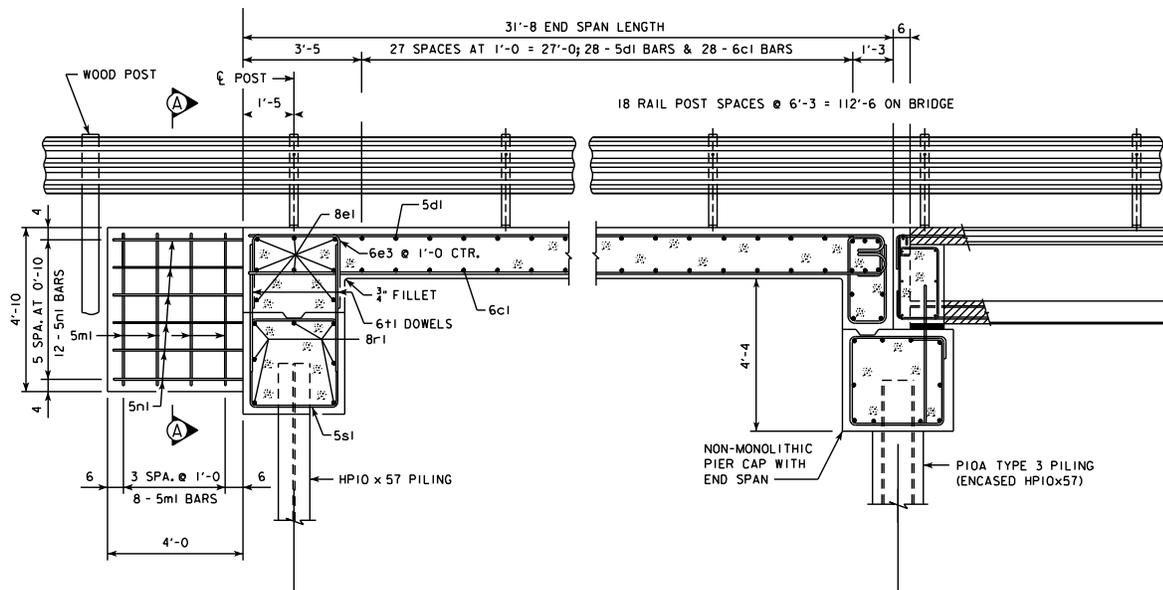


Figure 23. End span details of the Buchanan County Bridge

Casting

Design plans for the beams were finalized in the spring of 2008 and a contract was signed with Lafarge of North America to have the second generation pi-girders cast at their plant in Winnipeg, Manitoba, Canada. Two 25'-0" test beams were cast first and then three 51'-0" production bridge beams. The casting of the beams and construction of the bridge took place in the fall of 2008. To help reduce the cost of casting the beam, redi-mix trucks were used in the batching of the mix. Because of the uncertainty of using redi-mix trucks for the batching, the required compressive strength after steam curing was reduced to 21,500 psi. The batching process was a success with final average compressive strengths of close to 30,000 psi.

In the placement process, the girder bottom flange and web areas were fill first and then a trough was used to place the deck area. Personnel using reinforcing rods mixed the deck and web areas together while the deck was placed to prevent seams. See Figure 24 for casting with the trough and Figure 25 showing the steam curing of a girder. Steam curing was similar to the Wapello process of 48 hours at 195 degree Fahrenheit. Figure 26 shows a completed girder in the precasting yard.

The beams were fabricated in September 2008, while the contractor began mobilization, grading and substructure work. The beams were set in mid-October, and the end spans were poured a few weeks later. The project was completed in November, requiring 52 days from start to finish (with 53 having been assigned in the schedule). See Figures 27 and 28 for beam placement and the completed bridge. Load testing of the completed bridge was done in November of 2009 and the final report is pending.



Figure 24 Casting of Pi-Girder



Figure 25 Steam Curing of Pi-Girder



Figure 26. Completed Pi-Girder in Yard



Figure 27. Setting Pi-Girders in during Construction of the Bridge



Figure 28. Completed Pi-Girder Bridge

Wapello County (Waffle Slab Project)

In a continuation of the work with UHPC and with funding from a FHWA, Highways for Life Tech Partnership Grant, a third project is currently underway. Coreslab Structures of Omaha, Nebraska; Wapello County, Iowa; Iowa State University; Lafarge North America; FHWA and the Iowa Department of Transportation are teaming up on this third bridge project with additional funding from the Iowa Highway Research Board. The project will use precast deck panels cast with UHPC in a waffle configuration. See Figure 29 for details of a test panel. Phase I testing of the waffle slab is about complete. Once approved by the FHWA, Phase II will focus on a construction of a simple span 60 ft prestressed bridge in Wapello County, Iowa, using the approved UHPC waffle slab configuration. See Figure 32 for details of the proposed bridge cross section.

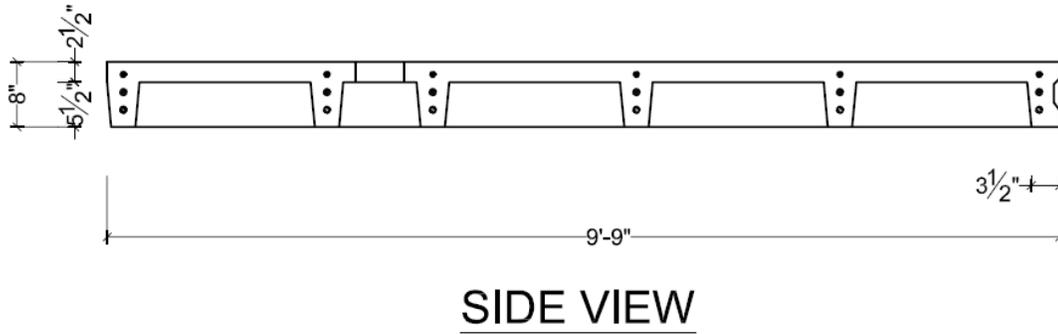


Figure 29. Side View Test Panel

The proposed waffle slab was jointly designed by the team and was based on a report done by FHWA (Graybeal 2008). Using the initial detail, the team developed a test panel to be load tested by ISU. See Figure 29, 30, and 31 for details. The test panel overall thickness including the web and slab is 8 inches with the deck thickness of 2 ½ inches (see Figure 30). Web spacing is approximately 1 ft 9 inches. Number seven reinforcing bars are used in the bottom mat of steel placed in the web and number six reinforcing bars are used in the top mat matching the spacing of the webs. The bars will project from the forms at the transverse joint location to provide ties. All joints and composite connections will be cast with UHPC fill.

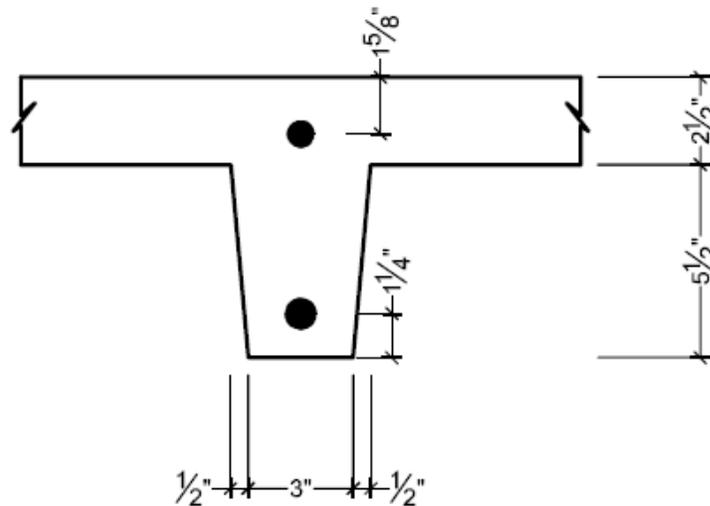


Figure 30. Typical Waffle Cross-Section

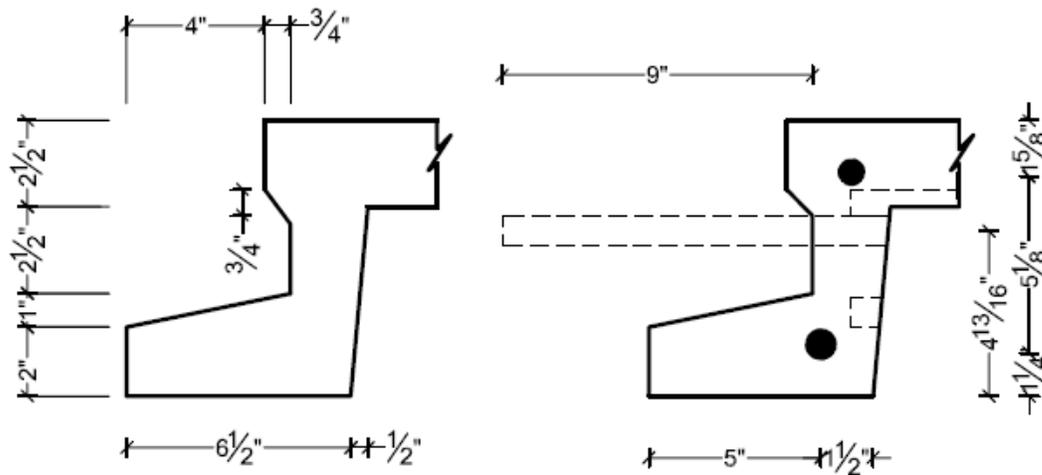


Figure 31. Typical Transverse Joint Detail

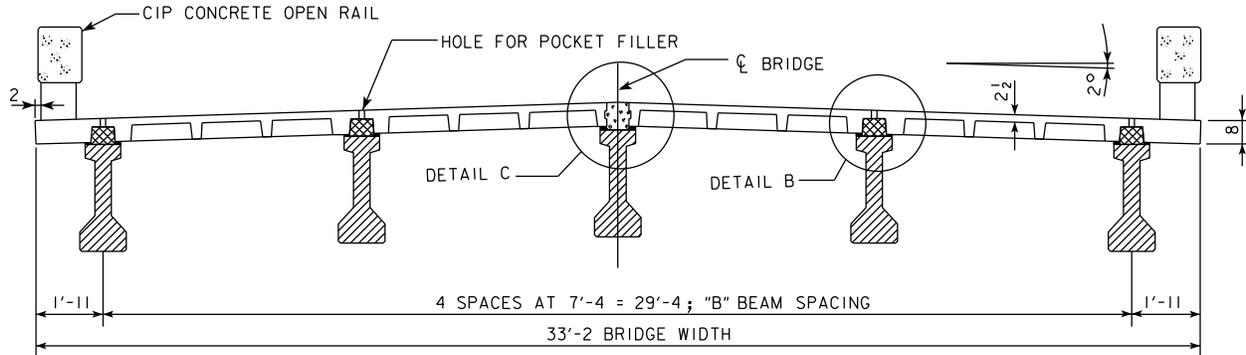


Figure 32. Cross Section of the Proposed UHPC Waffle Deck Bridge

Casting

Casting of two test panels took place in the fall of 2009 at the Coreslab precasting plant in Bellevue, Nebraska. The panels were cast upside down on a hinged table. The UHPC mix was placed using a trough similar to the Pi girder casting (see Figure 33). Once the mix was placed in the forms, the waffle forms were lowered into the main forms (see Figure 34). After the initial set, the forms were removed and the hinged table was tipped to remove the waffle panels (see Figure 35). Panels were then shipped to Iowa State University in Ames, Iowa, where they are currently being tested. At the writing of this report, testing is in progress and initial results are promising that the configuration will be approved by FHWA for use in the project.



Figure 33. Casting of a Waffle Test Panel



Figure 34. Placing Waffle Forms into the Main Panel Form



Figure 35. Removing Waffle Panel by Tipping of the Casting Table

CONCLUSION

This brief report has provided an summary of the bridge work that has been done to date in Iowa using ultra-high performance concrete. Based on the experience in Iowa, this new type of concrete mix has shown promising results when the sections are optimized to take advantage of the significantly high compressive strength and reduced volume of the UHPC. Future applications are being discussed to take advantage of the mixes high strengths, high durability and low permeability.

REFERENCES

- AASHTO. 2007. *AASHTO LRFD Bridge Design Specifications, 4th Edition*. Washington, DC: American Association of State Highway and Transportation Officials.
- Degen. 2006. Shear design and behavior of Ultra-High Performance Concrete, Masters Thesis, Iowa State University, 2006.
- Graybeal, B.A. and J.L. Hartmann. 2003. Strength and Durability of Ultra-High Performance Concrete. Paper presented at the Concrete Bridge Conference, Portland Cement Association.
- Gowripalan, N. and R.I. Gilbert. 2000. *Design Guidelines for RPC Prestressed Concrete Beams*. Sydney, Australia: School of Civil and Environmental Engineering, The University of New South Wales.
- Lafarge North America. 2009. <http://imagineductal.com>
- Lubbers, A.R. 2003. Bond Performance between Ultra High Performance Concrete and Prestressing Strands. Master Thesis, Ohio University.
- Graybeal, B.A. 2006a. Structural Behavior of Ultra-High Performance Concrete Prestressed I-Girders. FHWA-HRT-06-115. Washington, DC: Federal Highway Administration, McLean, VA.
- Graybeal, B.A. 2006b. Material Property Characterization of Ultra-High Performance Concrete. FHWA-HRT-06-103. Washington, DC: Federal Highway Administration, McLean, VA.
- Graybeal, B.A. 2009. Structural Behavior of Ultra-High Performance Concrete Pi-Girders. NTIS Report, PB2009-115495, National Technical Information Service, Springfield, VA.
- Graybeal, B.A. 2006a. Structural Behavior of a 2nd Generation UHPC Pi-Girder. FHWA-HRT-09-069. Washington, DC: Federal Highway Administration, McLean, VA.
- Graybeal, B.A., personal communication, 2006, 2007, 2008, and 2009.
- Perry, V., personal communication, 2006, 2007, 2008, and 2009.
- Ulm, F.J. 2004. *Bond and Shear Design of Iowa DOT Sampler Bridge*. Cambridge, MA: MIT.
- Wipf, T., B. Phares, S. Sritharan, B. Degen, and M. Giesmann, 2008. "Design and Evaluation of a Single-span Bridge Using Ultra-High Performance Concrete", Final Report to the Iowa Department of Transportation, 2008.