ULTRA HIGH PERFORMANCE CONCRETE HIGHWAY BRIDGE

Dean Bierwagen, PE, Methods Engineer, Office of Bridges and Structures, Iowa Department of Transportation
Norm McDonald, PE, Bridge Engineer, Office of Bridges and Structures, Iowa Department of Transportation

ABSTRACT

Wapello County and the Iowa Department of Transportation were granted funding through the TEA-21 Innovative Bridge Construction Program, (IBRC) for a project using ultra high performance concrete (UHPC). Plans using UHPC in the prestressed concrete beams for a bridge replacement project in Wapello County, Iowa have been prepared. The beams will be pretensioned using 0.6 inch diameter strands and without mild reinforcing steel, except to provide composite action with the cast-in-place deck. The research will include testing to verify shear and flexural capacities of a 70 ft long test beam along with shear testing of smaller beams.

Discussion of the design efforts and current progress of this research project are the focus of this presentation. Currently the 70 ft test beam and shear beams have been cast. Flexure and shear testing were successfully completed, and the three 110 ft. bridge beams were cast in June and July 2005. Construction of the bridge is planned for later in the fall.

Keywords: Ultra High Performance Concrete, Steel Fibers, Ductal Concrete, LaFarge North America, Bulb-Tee, and Reactive Powder Concrete

INTRODUCTION

Developed in France during the 1990's, ultra high performance concrete (UHPC) has seen limited use in North America. UHPC consists of 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, along with low permeability can be achieved depending on the curing process. To improve ductility, steel or fiberglass fibers (approximately 2% by volume) are added, replacing the use of mild reinforcing steel. For this project the patented mix (Ductal) developed by LaFarge North America has been used.

Research is currently being conducted at Ohio University, Michigan Technological University, Iowa State University, and Virginia Polytechnic Institute and State University to help better understand UHPC properties. Testing is on going at the Turner-Fairbanks Laboratory near Washington DC on a prototype prestressed pretensioned section (pi section). In addition, an IBRC project by the Virginia Department of Transportation using UHPC in prestressed beams for a highway bridge is underway.

PROJECT BACKGROUND

In 2003, Wapello County and the Iowa Department of Transportation were granted funding through the TEA-21 Innovative Bridge Construction Program, (IBRC) for a project utilizing ultra high performance concrete (UHPC). UHPC will be used in pretensioned prestressed concrete beams in a bridge replacement project in southern Wapello County, Iowa (see Figure 1, 2 and 3).

The beams will be pretensioned using 0.6-inch diameter low relaxation strands. No mild reinforcing steel except to provide composite action between the beam and cast-in-place deck will be used. To verify shear and flexural capacity of the beam, 10-inch and 12-inch shear beams, and a 71 ft long test beam have been cast. Testing is currently underway by Iowa State University (ISU) and the Center for Transportation Research and Education (CTRE) in Ames, Iowa. Currently the service capacity under flexure has been verified by testing, and casting of the 111 ft. production beams has been scheduled for June 26th, 2005. Letting of a separate project for the bridge construction is scheduled for June 20th, 2005.

BRIDGE DESCRIPTION

The replacement bridge for Wapello County will be a 110 foot simple span bridge with a three beam cross section. The abutments will be integral and an 8 inch cast-in-place deck will be used. Beam spacing will be 9 foot 7 inches with 4 foot 0 inch overhangs. See Figure 4 for additional details.

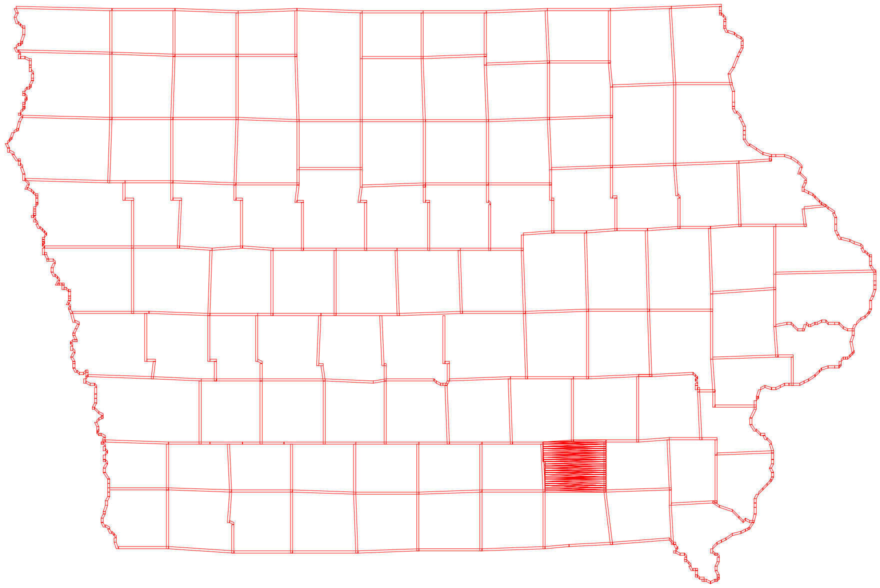

Figure 1. Project Location (Wapello County)

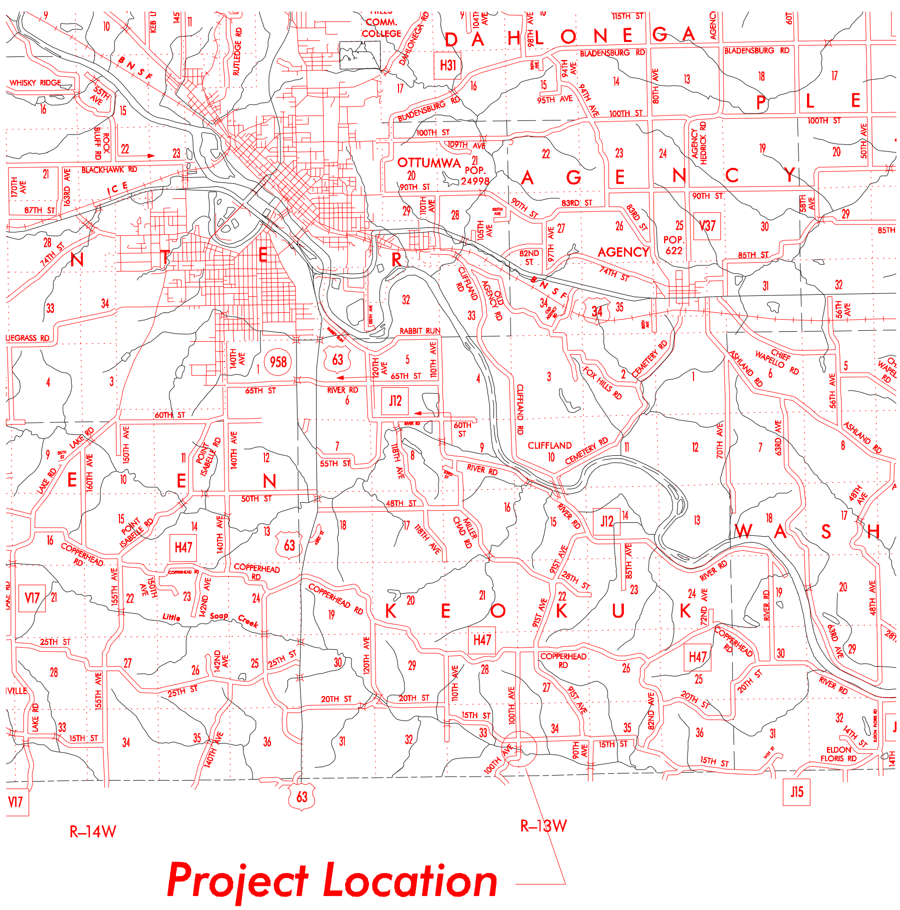

Figure 2. Project Location

Figure 3. Bridge Site

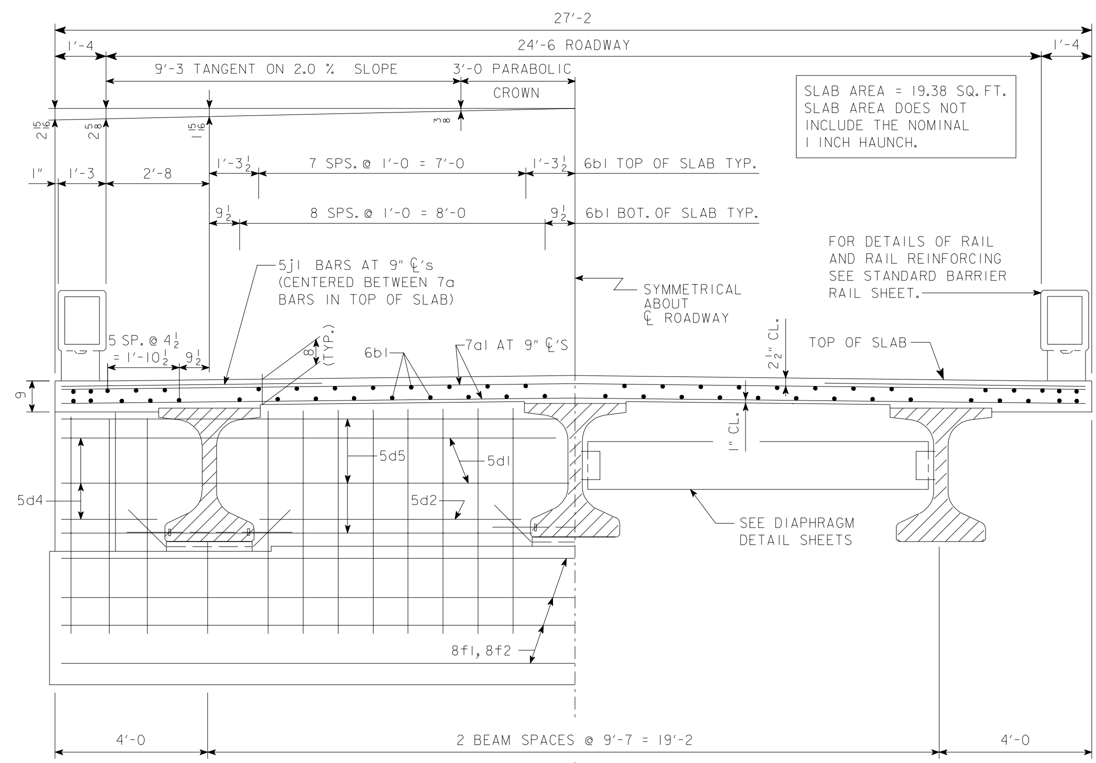

Figure 4. Proposed Bridge Cross Section

STAGES OF PROJECT

Because of the uniqueness of UHPC and the special requirements for designing, mixing, casting, and curing, this project was organized into stages as listed below to gain experience and confidence for all parties. Listed below are stages, completion dates, and current status.

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-foot test beam (Completed 2-23-05).
8. Flexure testing of 71-ft test beam (Completed 5-12-05).
9. Shear testing of 71-foot test beams (Completed 6-9-05).
10. Construction of replacement structure (Contract letting 6-20-05).
11. Casting of three 110-foot production beams (Completed 7-16-05).
12. Shear testing of shear beam specimens (Pending).Two year evaluation of finished bridge after construction.

PRELIMINARY WORK

Design Seminar

On August 12, 2003, the Iowa Department of Transportation and CTRE 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 Federal Highway Administration (FHWA) and attended by the FHWA, State, precast industry and academia. Speakers and topics are listed below:

1. Joey Hartmann, P.E., Turner-Fairbanks Highway, Research Center, FHWA, McLean, Virginia (Research Program)
2. Eugene Chuang, Ph.D., P.E., Garg Consulting Services, Inc, formerly from MIT, (Design Issues and Section Optimization)
3. Ben Graybeal, PSI, Inc.
(Material Testing)
4. Chris Hill, Prestress Services of Kentucky, Lexington, Kentucky
(Design Issues and Precasting)
5. Vic Perry, P.Eng., LaFarge North America, Calgary, Alberta, Canada
(Material Overview and Precasting Issues)
6. Brent Phares, Ph.D., ISU/CTRE, Ames, Iowa
(Overview of IBRC Project)

Test Batch at Materials Laboratory Ames, Iowa

On December 11^{th}, 2003, a test mix was produced at the Iowa DOT Materials Laboratory in Ames, Iowa. Personnel from the precasting industry, Iowa DOT, ISU and CTRE attended. LaFarge provided the test mix and Gavin Geist from LaFarge 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 (See Figure 5). Three inch by six inch test cylinders were cast along with four inch by four inch by eighteen inch beams. Specimens were cast on a vibrating table using a small plastic tremie tube. Curing of the specimens took place in sealed metal containers placed in ovens at 140 degrees F for 72 hours. Results of the test cylinder compressive strengths are shown in Table 2.

Table 1. Test Mix Proportions

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

Figure 5. Mixing of UHPC

Table 2. Compressive Strengths of 12-11-03 mix

Cylinder	Compressive Strength (psi)
1	15,896
2	16,123
3	20,004
4	15,943

Lower than expected compressive strengths (30,000 psi was expected) were found when the cylinders were tested, and the following reasons may have contributed to the reduced strengths:

1. Steam curing was started 24 hours after casting and before initial set had taken place. Without accelerators, initial set can take up to 40 hours.
2. There was difficulty in achieving plane ends of test cylinders for uniform compressive loading. The ends of the cylinders were trimmed with a concrete saw to provide square ends.
3. Visual inspection of a cylinder that was cut lengthwise showed higher than expected air voids.

Because of these problems, and to gain more experience working with the mix, the IDOT Materials Lab produced a second test batch on January 26th, 2004. Three by six inch test cylinders, and two-inch cubes. Casting of the two-inch cubes provided a test specimen with plane sides that did not require end preparation. Specimens were cured in sealed steel containers in ovens at 195 degrees F with 95% humidity for 40 hours (See Table 3 and Table 5) and in water (See Table 4). Compressive strengths of the cylinders improved, but were still lower than expected for the cylinders. Difficulty in achieving plane surfaces for uniform compression loading was believed to be the main cause of the lower strength values.

Table 3 (95% Humidity)

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

Table 4 (Water Cured)

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

Table 5 (95% Humidity Cured)

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

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 mix and cast the Ductal mix. Inspections of the plants were made as part of a certification process and test batches were performed at each plant.

Concerns expressed by precasters on the use of the Ductal mix are listed:

1. High cost for patented Ductal 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 steel fibers and fine aggregate.

3. Increased chances of damaging mixing equipment, due to the high mixing energy required.

4. Proper placement in forms and the requirement to produce the complete concrete quantity before placement can be started.

5. Because of the large amount of cement in the mix, shrinkage values were estimated to be twice the amount normally expected from standard mixes. Modifications of forms may be required to compensate for the additional shrinkage. Larger shrinkage will require properly timed release of the strands and removal of forms as well.

6. Long setting and curing time (40 hours set time / 48 hours of 195 degrees steam cure) and the lost production time in the casting beds

7. Lack of testing equipment required to:
    a. To evaluate the UHPC mix.
    b. To prepare the three inch by six inch test cylinders.
    c. For compressive testing of the two inch cubes.

Plant Selection

Bids were received from the local precastors for the casting of the 71 ft. test beam, three 111 ft production beams, and additional smaller beams for shear test. The cost submitted by the local precastors were higher than expected, due to the concerns listed above and the limited experience with UHPC mixes,. Therefore, the final precaster selected was LaFarge Canada Inc. of Greater Winnipeg Precast Division, Winnipeg, Canada.

Beam Design and Plan Preparation

CTRE, Wapello County and the Iowa Department of Transportation, Office of Bridges and Structures jointly designed the test beam, production beams and plans for the bridge. A modified Iowa 45-inch bulb tee was used. To save material in the beam section, the web width was reduced by two inches, top flange by one inch and the bottom flange by two inches (See Figure 6 and Figure 7). Because of the work that has been done by Dr. Ulm of MIT on UHPC, he provided a final review of the beam design.

The design of the beam was a challenge for the staff involved because of lack of approve specifications. Design guidelines have been developed by France, and design recommendations were available from reports that have been done. However, there are no specifications currently available in the United States. A review of the service and ultimate strength checks that were recommended by the French design guide and the research model developed by Dr. Ulm were used as a guide for design. The following additional design data was also 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 final beam design section used 49-0.6 inch strands stress to 72.6 percent of ultimate. To reduce end beam stresses five strands were draped along with debonding (See Figure 8 for strand layout). The 71 ft. test beam used an identical strand layout to verify release stresses.

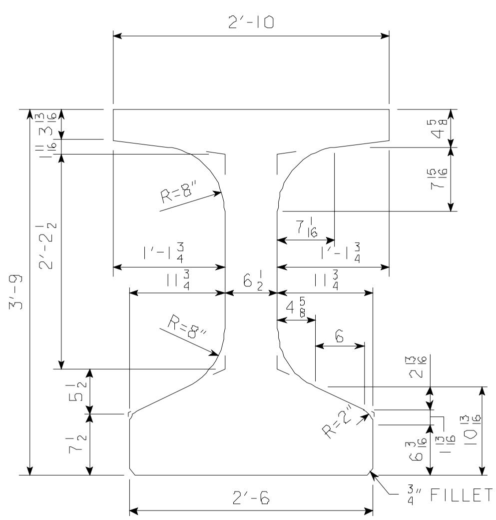

Figure 6. Iowa 45-inch Bulb Tee Section

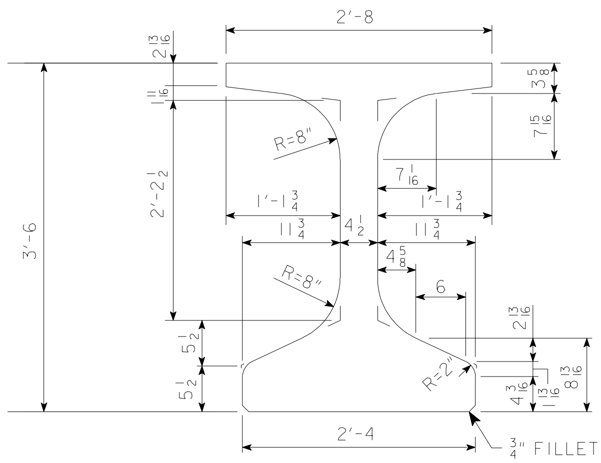

Figure 7. Modified Section for UHPC

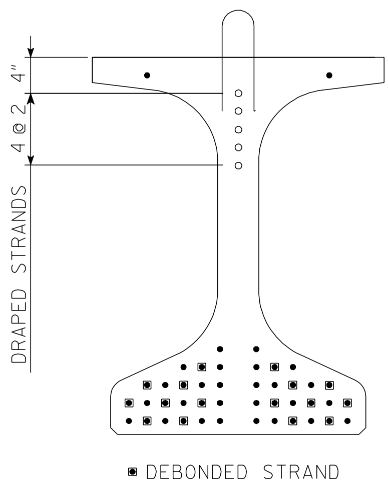

Figure 8. Strand Layout

OVERVIEW OF TEST BEAM

Casting and Release of Strands

1. Composite connection between the beam and cast-in-place deck

   The test beam was cast with three options for developing the composite connection between the beam and deck (See Figure 9). These options were studied due to the requirement that the top of the beam be covered with plastic immediately after placement of the concrete to prevent shrinkage cracks and the need for the plastic be placed directly on the concrete. Based on discussions after the casting, the use of the mild steel U-bar option was selected. The selection was based on the simplified detail and ease of installation during casting of the test beam.

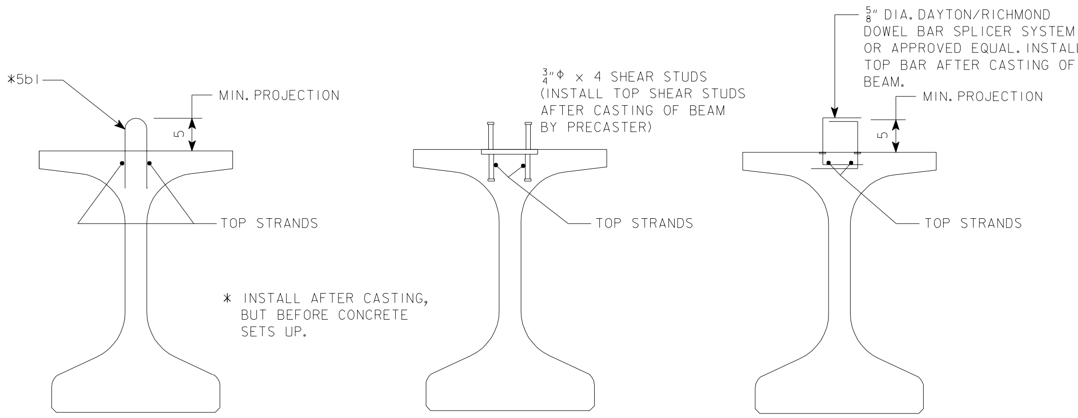

Figure 9. Composite connections

2. Strand anchorage and transfer of prestressing force

   Research completed at Ohio University, "Bond Performance Between Ultra-High Performance Concrete and Prestressing Strands" showed improved bond strength using UHPC. Because of the improved bond and transfer there was concern that the reduced transfer lengths (possibly less than 12 inches) may cause a concentration of release forces at the interface between the bottom flange and web. To reduce these forces both debonding and draping of the strands were provided (See Figure 8 for details). Under inspection no visible cracks were found at the interface after release of the strands for the test beam.

3. Short term and long term losses

   To try and measure losses in the beam, fiber optic strain gauges were attached to the bottom row of strands on the test beam before casting. Based on the changes in strain measured at release and the final strains after curing the release losses and total losses at midspan were calculated. Final losses were calculated to be approximately 27 percent higher than those estimated in design.

4. Camber and Growth

   Release camber for the 71 ft test beam was 1 3/8 inch. After curing the measured camber was 3 1/8 inches. No additional growth was noted in the ISU lab after shipment.

5. Release and Final Compressive Strengths (percent difference)

   Beam strands were released at initial concrete strengths of 14,500 psi. Final compressive strengths from 3 inch x 6 inch test cylinders varied from 20,400 ksi to 33,700 psi with an average of 28,976 psi. Lower values of compressive strengths may have been due to poor end cylinder preparation.

Flexure Test

The initial flexure test was limited to just over the concrete cracking load. There was concern that flexure testing to failure might adversely effect the ultimate shear test at the beam ends. The test was performed on May 12, 2005 in the structures lab at Town Engineering, ISU. Four jacks were placed symmetrically at midspan spaced 2.6 ft and 4.5 ft from the centerline of the span. See Figure 10. 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. See Figure 11 Maximum load that was applied was 264 kips with 3 ¼ inches of deflection. See Figure 12 for load displacement diagram.

Figure 10. Flexure Test

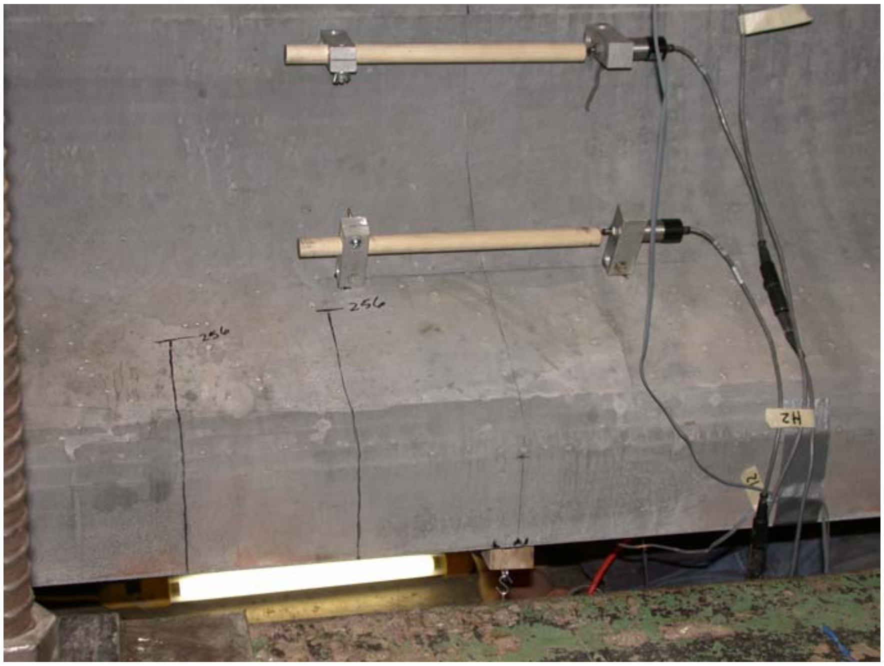

Figure 11. Measured flexure cracking at midspan

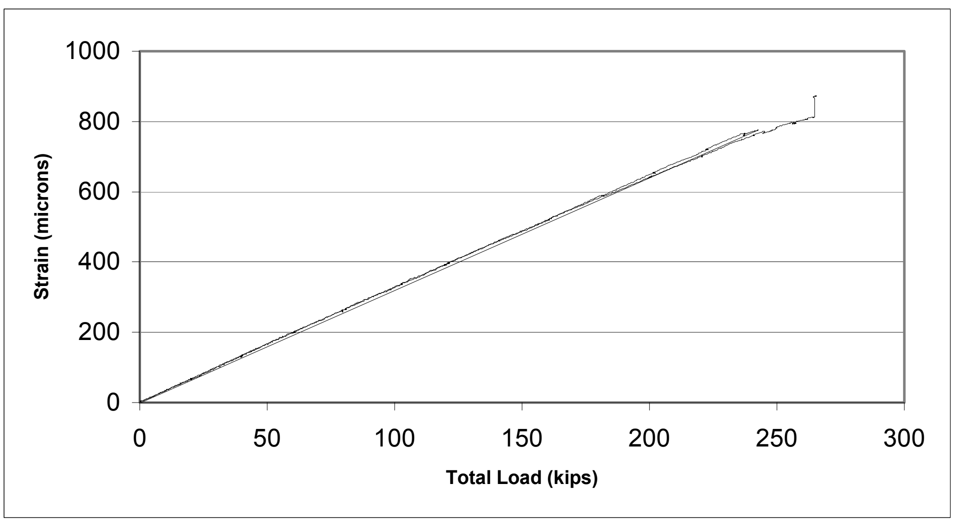

Figure 12. Midspan fiber optic gauge

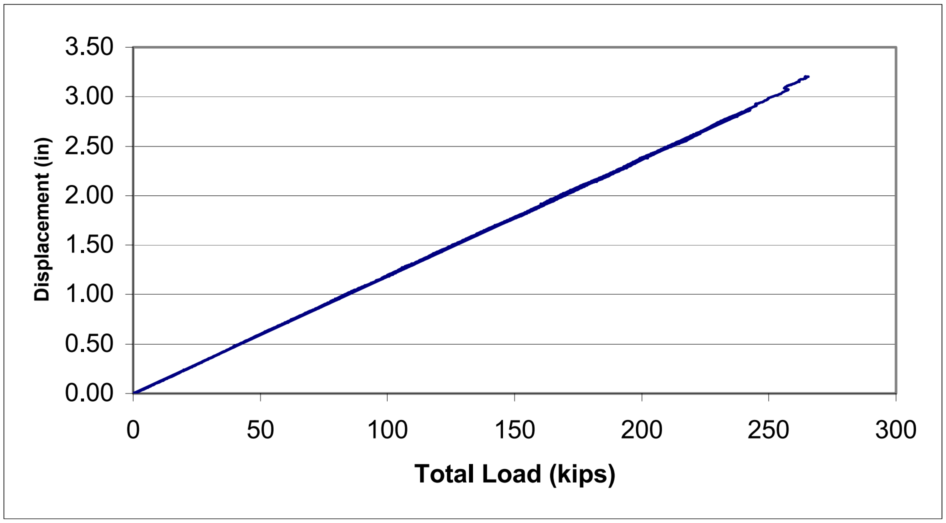

Figure 13. Midspan deflection gauge

Shear Test

The shear test was performed on June 9th, 2005 (See Figure 14 for overall layout). Shear cracking developed at a total load of 370 kips or 315 kips of shear at the end. Total load applied at failuire was 594 kips or 501 kips of shear at the beam end (See Figure 15 for failed beam end). In addition to the shear cracking the beam end also split down the centerline of the beam section (See Figure 16). The reason for this split is still under investigation.

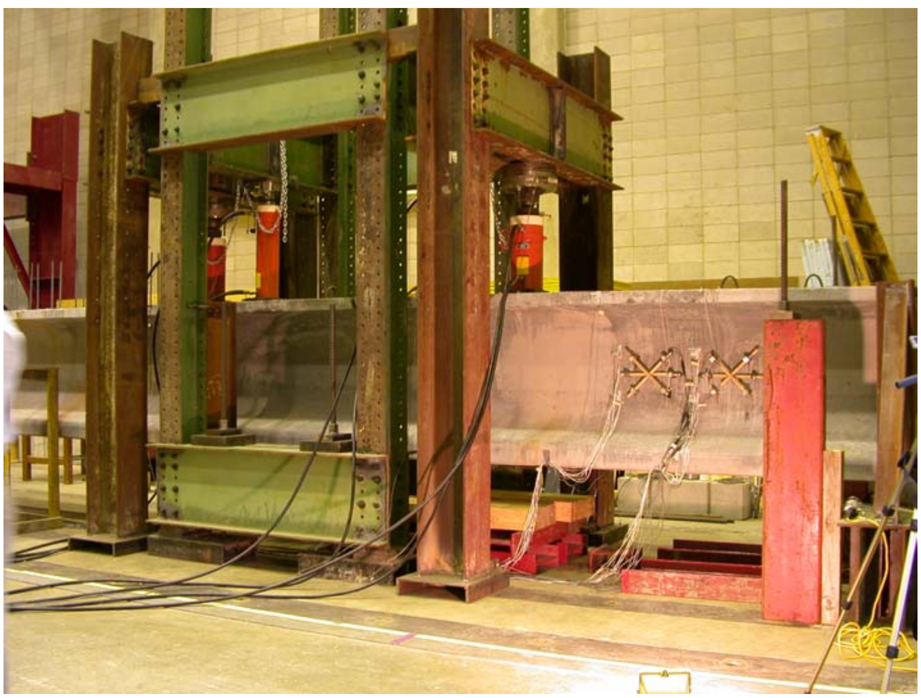

Figure 14. Shear test setup.

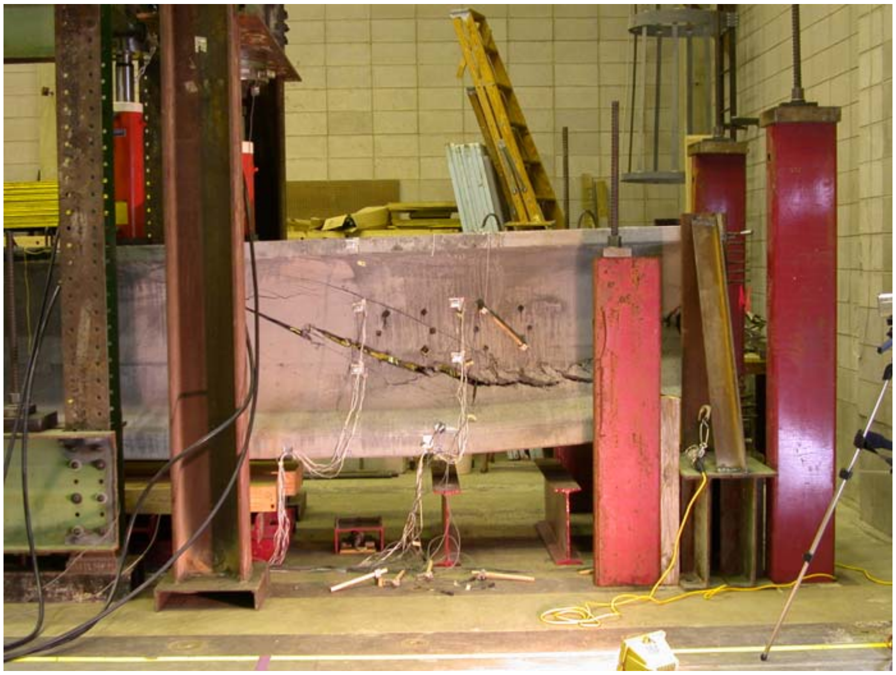

Figure 15. Failed end section.

Figure 16. Split beam end.

Additional Shear Testing

To help develop a better understanding of the shear capcacity of the UHCP mix, additional shear testing was included as part of the research. Shear tests will be performed on a series of smaller beam shapes (10-inch deep by 54-inch long and 12-inch deep by 64-inch long) with web widths from 1 ½ to 2-inches. See Figure 17 and 18 for dimensions and photo of the test specimens.

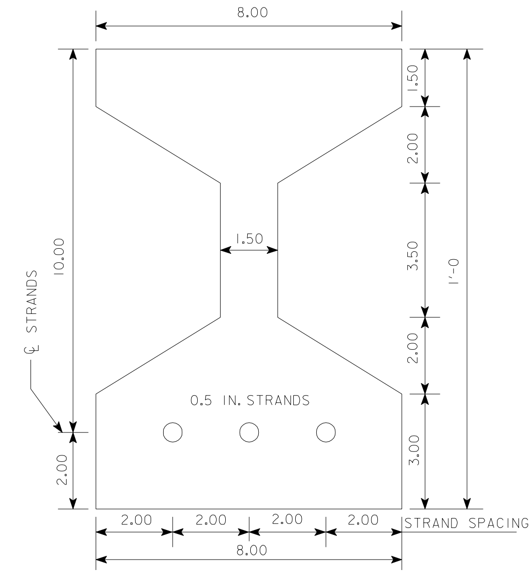

Figure 17. 12 inch shear beam cross section

Figure 18. 10 inch and 12 inch shear beams at ISU

Production Beams for Bridge Project

Production beams for the bridge were cast at the LaFarge plant in Winnipeg, Canada on June 25th, July 9th and July 16th. Fiber optic gauges were installed on the final beam that was cast to measure strains at release, construction and final dead and live load. The completed bridge will be evaluated for two years.

Conclusion

This IBRC project has allowed the Wapello County, Iowa Department of Transportation, CTRE and Iowa State University the opportunity to gain valuable experience designing, testing, mixing, and casting ultra high performance concrete. Additional research in the future will need to address current design and production concerns, and develop more efficient beam designs to maximize UHPC unique structural properties. Additional research is already underway to use UHPC in precast replacement paving notches as part of a rapid approach slab replacement work repair.