

Ultra High Performance Concrete Highway Bridge

Dean Bierwagen
Office of Bridges and Structures
Iowa Department of Transportation
800 Lincoln Way
Ames, IA 50010
Dean.Bierwagen@dot.state.ia.us

Ahmad Abu-Hawash
Office of Bridges and Structures
Iowa Department of Transportation
800 Lincoln Way
Ames, IA 50010
Ahmad.Abu-Hawash@dot.state.ia.us

ABSTRACT

Wapello County and the Iowa Department of Transportation were granted funding through the TEA-21 Innovative Bridge Construction Program to demonstrate the use of ultra high performance concrete (UHPC) in a bridge replacement project. The UHPC in the prestressed concrete beams is expected to achieve a 28-day compressive strength of up to 30,000 psi. The use of this innovative product in a three-beam cross section is intended to take advantage of the superior strength and to optimize design. 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.

In Phase I of the multi-phase project, a 71-foot-long test beam will be tested to verify shear and flexural capacities, along with shear testing of smaller beams. If testing efforts are successful, Phase II will include the casting of 111-foot-long beams, followed by the construction of the single span bridge in the spring/summer of 2005. After construction, a monitoring program will be implemented to document the performance of this innovative product.

A discussion of the design efforts and the current progress of this research project is the focus of this paper.

Key words: bulb-tee—ductal concrete—reactive powder concrete—steel fibers—ultra high performance concrete

INTRODUCTION

Developed in France during the 1990s, 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 and 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 mild reinforcing steel. For this project, a 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 under way at the Turner-Fairbanks Laboratory near Washington, DC on a prototype prestressed, pretensioned section. In addition, a TEA-21 Innovative Bridge Construction Program (IBRC) project, using UHPC in prestressed beams for a highway bridge, is underway for the Virginia Department of Transportation.

PROJECT BACKGROUND

In 2003, Wapello County, Iowa and the Iowa Department of Transportation were granted funding through the IBRC for a project utilizing UHPC. UHPC will be used in pretensioned, prestressed concrete beams in a bridge replacement project in southern Wapello County (see Figures 1, 2, and 3).

The beams will be pretensioned using 0.6-inch diameter low relaxation strands. No mild reinforcing steel, except an amount 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-foot-long test beam have been cast. Testing is currently underway at Iowa State University 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-foot production beams has been scheduled for June 26, 2005. Contract letting for a separate project for the bridge construction is scheduled for June 20, 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 feet 7 inches with 4-foot overhangs. See Figure 4 for additional details.

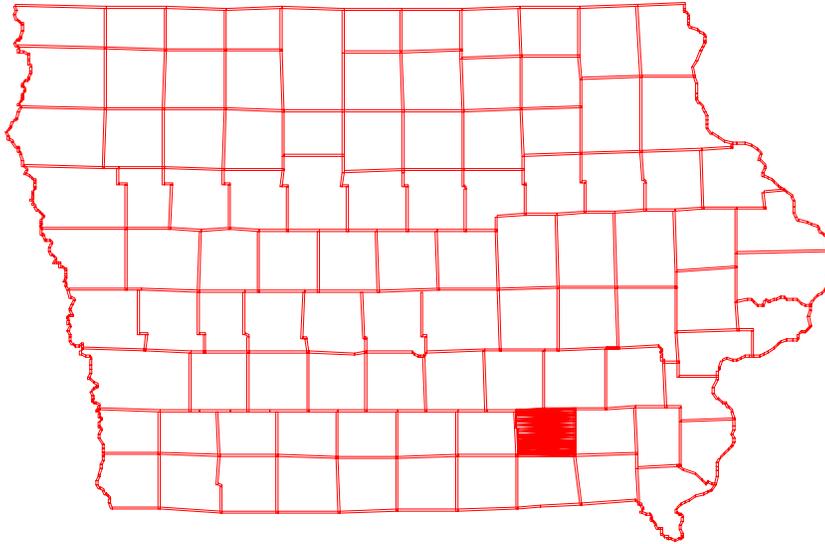
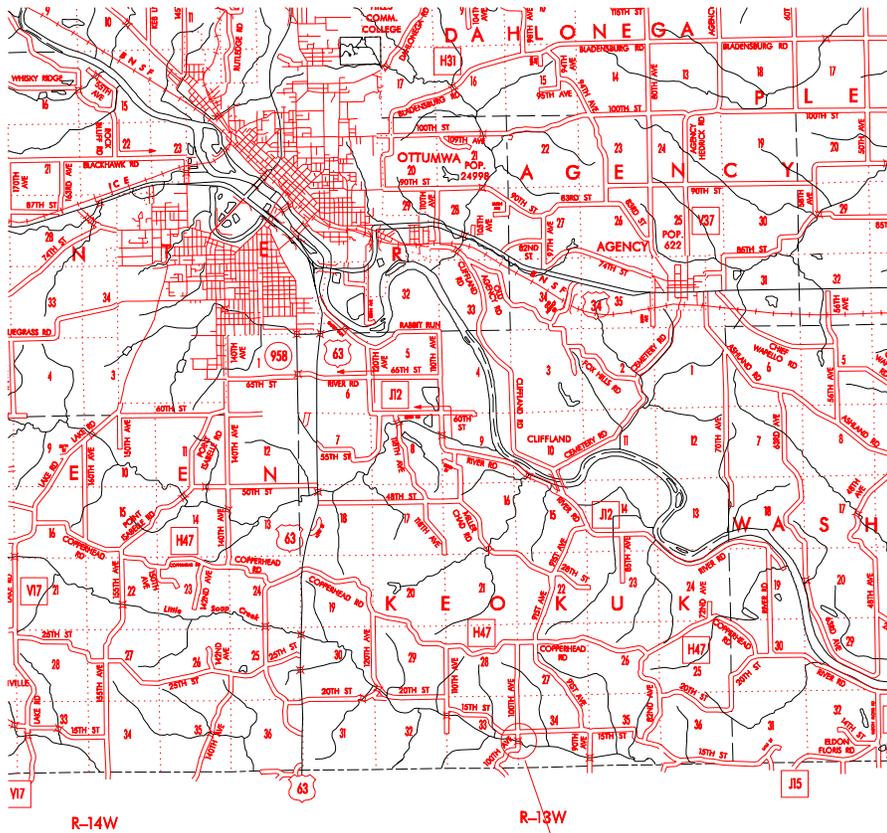


Figure 1. Wapello County, Iowa



Project Location

Figure 2. Project location in Wapello County, Iowa



Figure 3. Bridge site

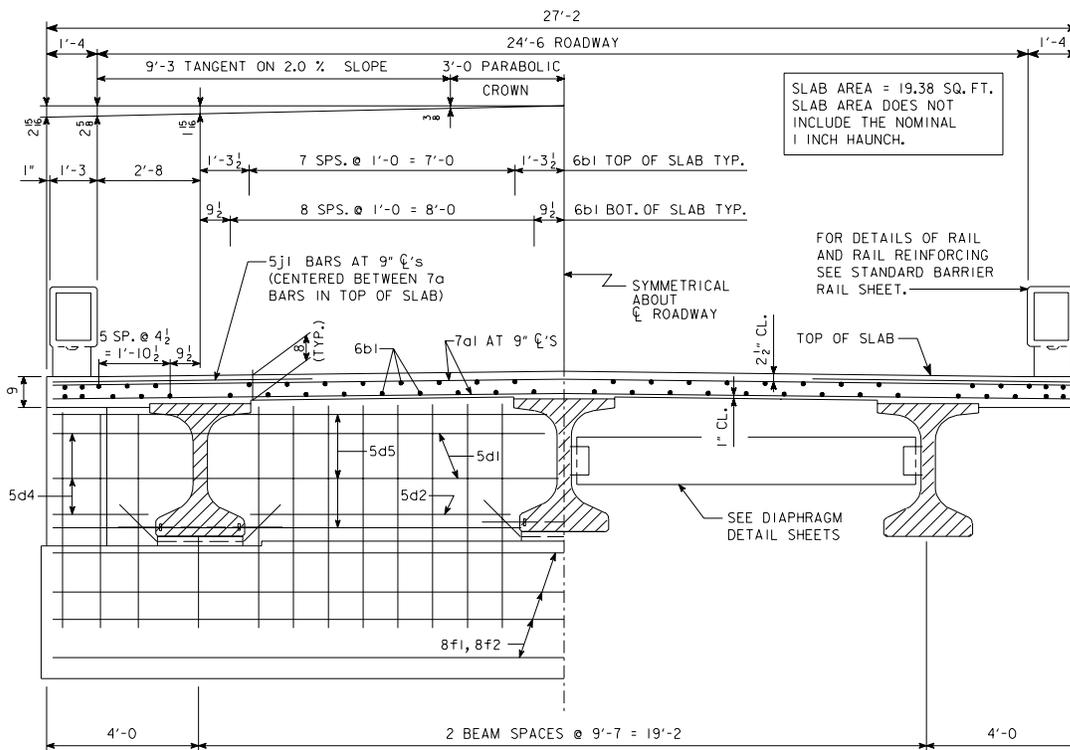


Figure 4. Proposed bridge cross section

STAGES OF PROJECT

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

1. Ultra-High Performance Concrete Design Seminar (completed 8-12-03)
2. Test batch at Iowa DOT 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-foot test beam (completed 5-12-05)
9. Shear testing of 71-foot test beam (scheduled 6-9-05)
10. Shear testing of shear beam specimens (pending)
11. Casting of three 111-foot production beams (scheduled to begin 6-26-05)
12. Construction of replacement structure (contract letting scheduled for 6-20-05)
13. Two-year evaluation of finished bridge after construction

PRELIMINARY WORK

Design Seminar

On August 12, 2003, the Iowa DOT and CTRE organized a seminar on ultra high performance concrete to provide information to people who would be involved in the project. The seminar was sponsored by the Federal Highway Administration (FHWA) and attended by individuals from the FHWA, the state of Iowa, the precast industry, and academia. Speakers and topics are listed below:

1. Joey Hartmann, P.E., Turner-Fairbanks Highway Research Center, FHWA
(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
(Design Issues and Precasting)
5. Vic Perry, P. Eng., LaFarge North America
(Material Overview and Precasting Issues)
6. Brent Phares, Ph.D., CTRE
(Overview of IBRC Project)

Test Batch at Materials Laboratory in Ames, Iowa

On December 11, 2003, a test mix was produced at the Iowa DOT Materials Laboratory in Ames, Iowa. Personnel from the precasting industry, Iowa DOT, Iowa State University, 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 ft capacity was used to produce a one-cubic ft batch (see Figure 5). Three-inch by six-inch test cylinders were cast along with four-inch by four-inch by 18-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° 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
3000 NS (super plasticizer)	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. 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 Iowa DOT Materials Lab produced a second test batch on January 26, 2004. Three-inch by six-inch test cylinders and two-inch cubes were prepared. 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° F with 95% humidity for 40 hours (see Tables 3 and 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. Specimens at 95% humidity

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

Table 4. Water-cured specimens

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

Table 5. Specimens cured at 95% humidity

Three-inch x six-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. Longer time needed 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. Shrinkage values estimated to be twice the amount normally expected from standard mixes, because of the large amount of cement in the mix. 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° F steam cure) and the lost production time in the casting beds
7. Lack of testing equipment required to do the following:
 - Evaluate the UHPC mix
 - Prepare the three-inch by six-inch test cylinders
 - Compressive testing of the two-inch cubes

Plant Selection

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

Beam Design and Plan Preparation

CTRE, Wapello County, and the Iowa DOT 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 Figures 6 and 7). Because of the work on UHPC been done by Franz-Josef Ulm of the Massachusetts Institute of Technology, 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 approved 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 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 were 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 stressed to 72.6% of ultimate. To reduce end-beam stresses, five strands were draped along with debonding (see Figure 8 for strand layout). The 71-foot test beam used an identical strand layout to verify release stresses.

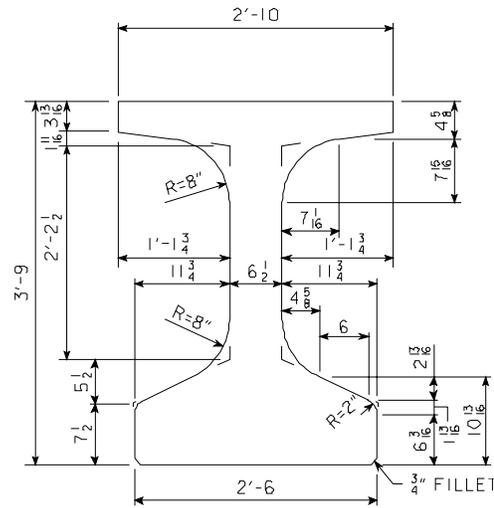


Figure 6. Iowa 45-inch bulb tee section

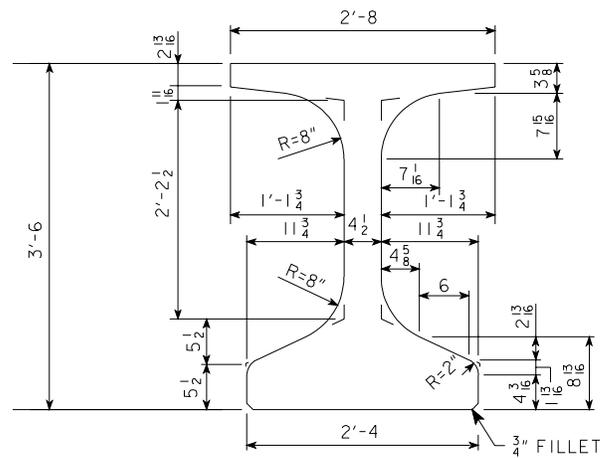


Figure 7. Modified section for UHPC

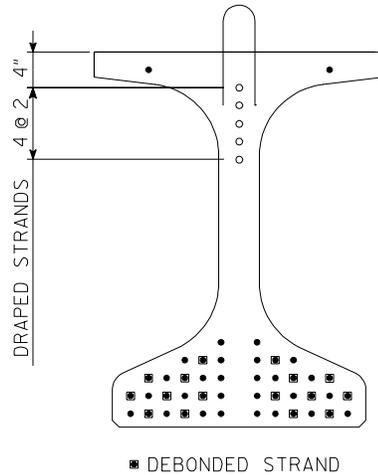


Figure 8. Strand layout

OVERVIEW OF TEST BEAM

Casting and Release of Strands

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.

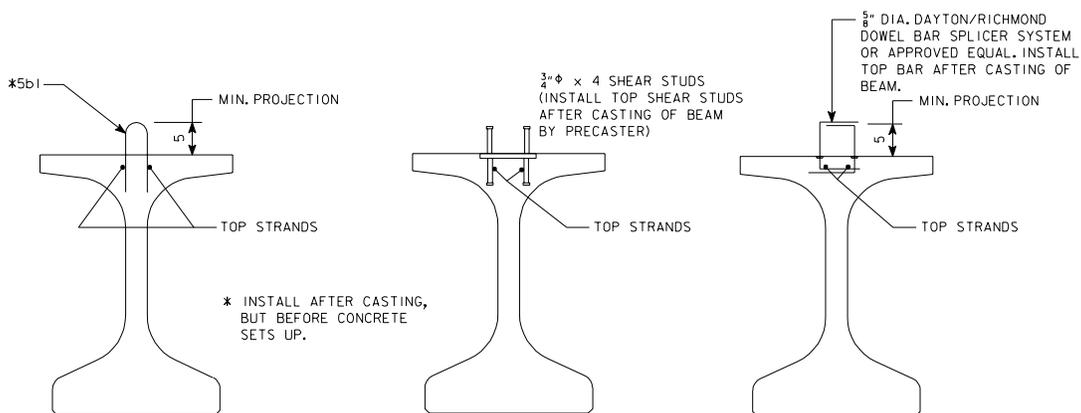


Figure 9. Composite connections

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.

Short-Term and Long-Term Losses

To attempt to 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% higher than those estimated in design.

Camber and Growth

Release camber for the 71-foot test beam was 1-3/8 inches. After curing, the measured camber was 3-1/8 inches. No additional growth was noted in the Iowa State University lab after shipment.

Release and Final Compressive Strengths (Percent Difference)

Beam strands were released at initial concrete strengths of 14,500 psi. Final compressive strengths from three-inch x six-inch test cylinders varied from 20,400 psi 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, Iowa State University. Four jacks were placed symmetrically at midspan, spaced 2.6 feet and 4.5 feet from the centerline of the span. See Figure 10. The 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. The maximum load applied was 264 kips with 3¼ inches of deflection. See Figure 12 for a load displacement diagram.

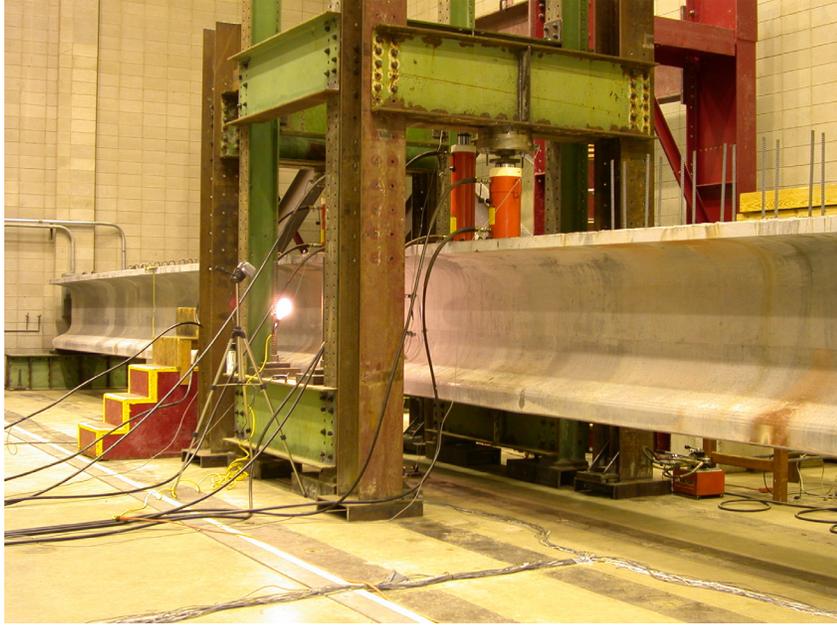


Figure 10. Flexure test

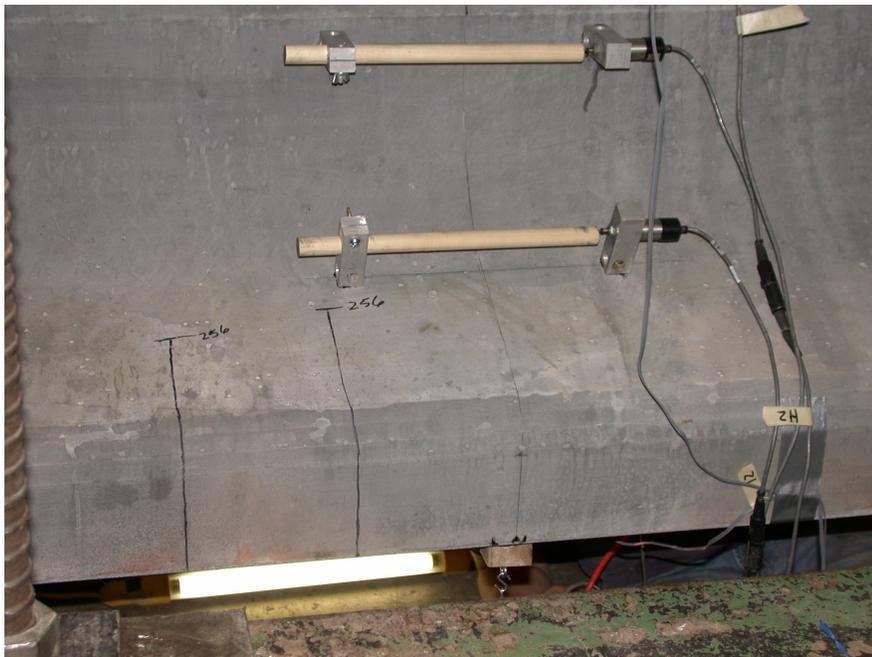


Figure 11. Measured flexure cracking at midspan

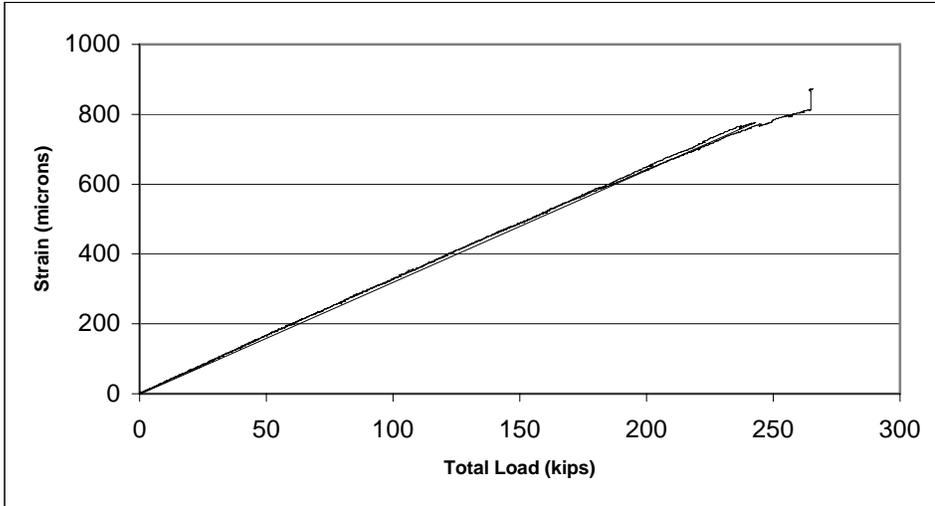


Figure 12. Midspan fiber optic gauge

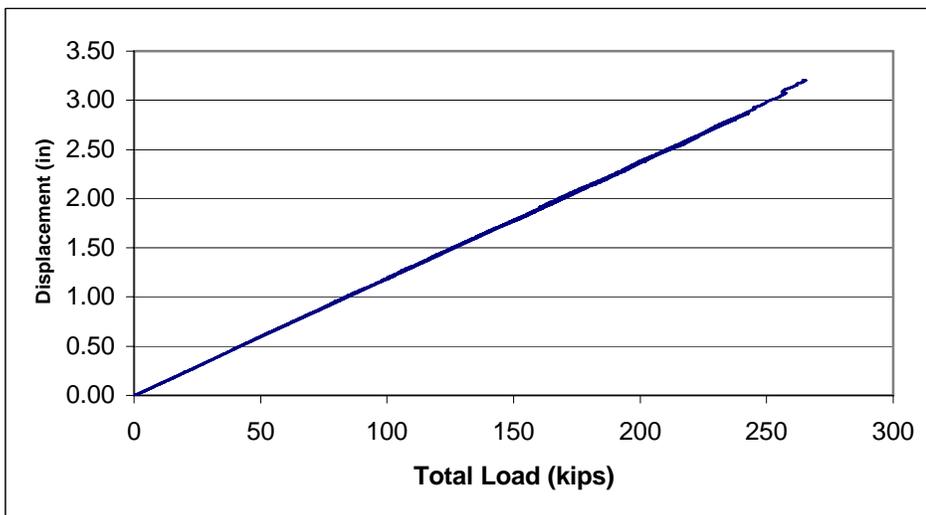


Figure 13. Midspan deflection gauge

Shear Test

At the writing of this report, shear testing had not taken place, but was scheduled for June 9, 2005. An estimated failure load of 750 kips has been calculated.

To help develop a better understanding of the shear capacity 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 1½ to 2 inches. See Figures 14 and 15 for the dimensions and a photo of the test specimens.

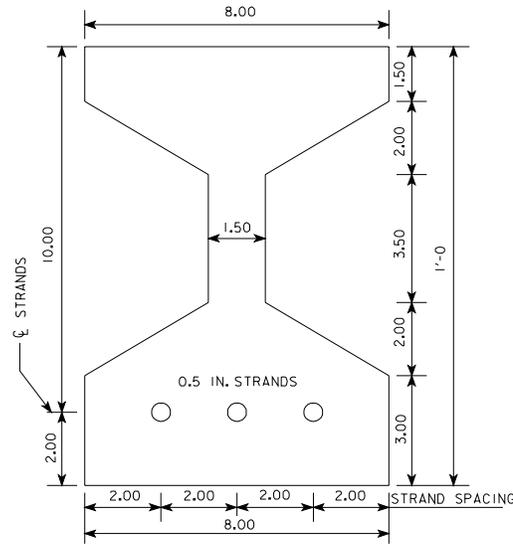


Figure 14. Twelve-inch shear beam cross section



Figure 15. Ten-inch and 12-inch shear beams at Iowa State University

CONCLUSIONS

This IBRC project has given Wapello County, the Iowa DOT, 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 should address current design and production concerns, and develop more efficient beam designs to maximize the unique structural properties of UHPC. Additional research is already underway to use UHPC in precast replacement paving notches as part of rapid approach slab replacement work repair.