



Iowa's ultra-high performance concrete implementation Bridging gaps in structural materials and design

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Several U.S. transportation organizations have identified a critical need for research and development of more durable bridges. As a result, the Federal Highway Administration (FHWA) and other transportation funding agencies have investigated and developed programs to support research of new and innovative materials.

The advanced properties of ultra-high performance concrete (UHPC) provide various opportunities for development of new structural shapes and bridge applications focused on addressing important infrastructure issues. Topics such as creating longer-lasting bridges through enhanced durability or allowing for the spanning of longer distances with more shallow superstructures can be addressed using UHPC. In a systematic sense, UHPC also presents ways to create new structural forms that facilitate accelerated construction and rapid renewal of the highway infrastructure.

A number of UHPC building and bridge projects have been constructed since it was first developed in France during the early 1990s. A pedestrian bridge (the oldest UHPC bridge), was built in Quebec, Canada, in 1997; precast UHPC beams have also been used in nuclear power plant construction since 2000. Another pedestrian bridge (South Korea) and the first highway bridge (France) were constructed using UHPC in 2002. Over the last decade, FHWA, several state departments of transportation and U.S. research universities have begun investigating UHPC use for bridge applications in the United States (**Figure 1**).



Figure 1 – The first UHPC bridge built in the United States is located in Wapello County, Iowa.

The Iowa Department of Transportation (DOT) has particular interest in advanced materials development for more durable bridges. Recognizing that little technical information exists and no standard design specifications are available for bridge design using UHPC, Iowa has collaborated with local, national and international entities to develop and conduct UHPC research, implementing UHPC in several recent demonstration projects in Iowa.

Nationally, Iowa has partnered with FHWA through the Innovative Bridge Research and Construction/Deployment (IBRC/IBRD) programs and the Highways for Life (HfL) initiative, working closely with investigators at the FHWA Turner-Fairbank Highway Research Center in Washington, D.C., to test and share UHPC technical information.

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Ductal® UHPC is comprised of preblended, dry-mix ingredients, small fibers and a superplasticizer.

Components

UHPC consists of fine sand, cement, silica fume and quartz flour in a dense, low-water cementitious materials ratio (0.15 to 0.19) mix. Compressive strengths of 18,000-30,000 psi can be achieved depending on the mixing and curing process. The material has low permeability and high durability. To improve ductility, steel or polyvinyl alcohol (PVA) fibers (approximately 2 percent by volume) are added, replacing the mild steel reinforcement. For bridge projects in Iowa, the patented mix Ductal® marketed by Lafarge North America was used with steel fibers.

UHPC projects in Iowa

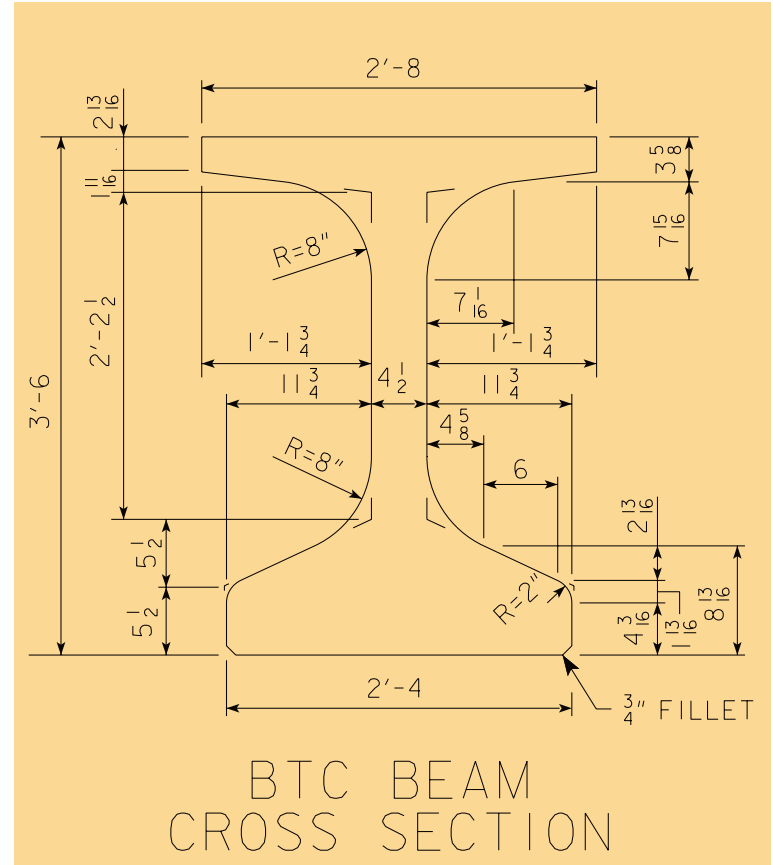
UHPC I-shaped girder bridge Wapello County, Iowa



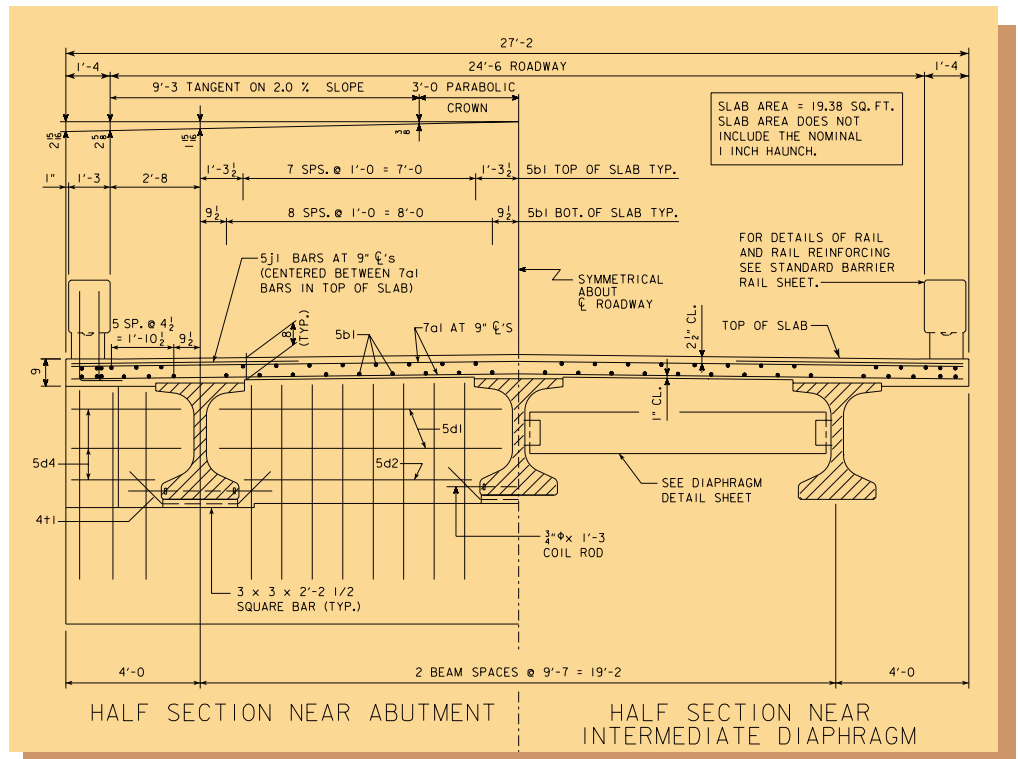
Figure 2 – Mars Hill Bridge, Ottumwa, Iowa

The Iowa DOT worked cooperatively with Wapello County and Iowa State University’s (ISU) Bridge Engineering Center (BEC) to design, construct and evaluate the first UHPC bridge built in the United States. Completed in 2006, this was the Iowa DOT’s initial experience with bridge design using UHPC material. Because standardized design specifications did not exist for UHPC girders at that time, the Iowa DOT developed an experimental testing program to verify design assumptions (Iowa Highway Research Board [IHRB] project TR-529, “Design and Evaluation of a Single-Span Bridge Using Ultra-High Performance Concrete”). Prior FHWA laboratory testing of UHPC I-shaped girders also provided useful background information for this project.

The UHPC mix was used in fabricating three full-scale, modified Iowa bulb-tee girders. The bridge girders were 111-feet long, prestressed concrete bulb-tees used in a 110-foot single span, integral abutment bridge replacement project known as the Mars Hill Bridge, located south of Ottumwa, Iowa (**Figure 2**).



Modified BTC section for Mars Hill Bridge



Cross section of Mars Hill Bridge

The bridge has an overall roadway width of 24 feet 6 inches. Other bridge components were cast using conventional concrete materials. Material tests (small- and full-scale beam tests with a length of 71 feet), were performed at ISU's Structural Engineering Laboratory prior to construction that supported the initial design assumptions. After construction of the bridge, field load tests were performed to further validate the design assumptions and provide additional structural performance information (Figure 3).

This UHPC I-shaped girder bridge project provided the Iowa DOT a better understanding of this new material's characteristics (from a design, fabrication and construction standpoint) to determine if UHPC might be a long-term solution for building more durable bridges. The laboratory testing and subsequent field testing of the completed bridge provided validation of the design procedure and more information on flexural, shear and shear/flexure of an I-shaped girder. The long-term performance of the bridge will be assessed and provide insights into potential increased structure durability and associated cost-effectiveness associated with use of UHPC components. Iowa DOT engineers continue sharing results and information gained from this project with other bridge and transportation agencies throughout the United States and the world.



Laboratory loading test setup evaluates flexural/shear characteristics of a full-scale beam.

Figure 3 – Testing of small-scale shear beams

Learn More

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For more information on UHPC bridge projects, visit the Iowa DOT's Office of Bridges and Structures website at:

iowadot.gov/bridge/ibrcibrd_research.htm

UHPC pi-shaped girder bridge Buchanan County

Given the relatively high unit cost of UHPC, the FHWA investigated using the material for bridges with a more cost-effective cross section. Based on analytical evaluations, a first-generation pi-shaped girder (as in Greek letter π) was determined optimum. Specific dimensions were developed for the pi-shaped girder for bridge spans approximately 70 to 100 feet. The FHWA Research Center performed laboratory and field testing to further assess the potential use of the shape for bridge structures. Testing indicated that some modifications to the cross section were needed — not due to strength issues, but primarily from a service standpoint (e.g., potential cracking and a sturdier cross section).

A second generation pi-shaped girder was developed by FHWA in cooperation with the Iowa DOT and ISU's BEC using finite element analysis. To validate the new design shape, a laboratory test using a full-scale girder and a field test of a bridge constructed with the pi-shaped girder were performed.

The Jakway Park Bridge in Buchanan County is the first bridge constructed in the United States using a second generation prestressed, pi-shaped girder composed

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“Specific dimensions were developed for the pi-shaped girder for bridge spans approximately 70 to 100 feet.”

The 50 foot (15.2m), single span girder is supported on plain neoprene bearing seats with beam ends encased with cast-in-place concrete diaphragms. The two end spans were cast-in-place, reinforced concrete slabs with integral abutments supported on steel piles. The pier caps are supported on steel piles encased in concrete. The use of the pi-shaped girders provided a complete superstructure system and eliminated the need for an independent deck. A 3/8 inch asphalt chip seal was applied to provide texture.

Once the bridge girder construction was complete, intermediate steel tube diaphragms were placed at each quarter point. The diaphragms were placed between each girder bottom flanges to provide lateral support to the girder webs. During diaphragm installation, strain data were measured on the girder webs for potential out-of-plane bending. (Figure 7).



Figure 7 – Field instrumentation and monitoring were used in a live-load field testing process to assess the condition of the recently constructed Jakway Park Bridge.

Two field load tests on the completed bridge (only the pi-shaped girder span) were performed: one immediately after construction, and the other approximately one year after construction. Strain and deflection data were collected and evaluated using a controlled truck loading. Field tests indicated that the bridge would perform well when opened to traffic (Figure 8).



Figure 8 – The completed bridge was open to traffic on November 26, 2008.

Construction monitoring of the UHPC bridge components and diaphragms allowed assessment of structural performance for the relatively thin girder webs. The live-load field testing of the completed bridge provided validation of the design assumptions and prediction of the finite element model.

The data collected provides important technical information for the development of standardized design procedures for bridges using pi-shaped girders. Many cutting-edge developments generated from this project will benefit the transportation industry.

There were many challenges associated with this project, including the absence of specific design procedures; however, the finite element analysis supported the development of a second generation pi-shaped girder. Studies show this new girder shape contributes to a more durable bridge element.

UHPC in critical ABC bridge joints Pottawattamie County, Iowa

A national research study related to accelerated bridge construction (ABC), titled “Innovative Bridge Designs for Rapid Renewal,” is in progress. The overall objective is to recommend ways ABC can be utilized as a tool in the renewal process to reconstruct existing bridge networks in a timely and cost-effective way. Of particular focus is the identification of cost-effective construction methods using precast bridge elements that also provide improved durability for the constructed bridge. The Iowa DOT is a cooperating partner in the study being led by HNTB Corp. (the Strategic Highway Research Program, SHRP2-Project R04, is the funding agency).

A critical part of this study is to design and construct a demonstration bridge in Iowa (replacing an existing bridge) consisting of superstructure and substructure precast elements composed primarily of conventional and high strength concrete. The 210 foot 2 inch, three-span bridge will be 47 feet 2 inches wide and comprised of steel/precast modular units with precast bridge approaches. A site has been selected for this project on U.S. 6 over Keg Creek in Pottawattamie County, just east of Council Bluffs. The project was let Feb. 15, 2011. The existing bridge will be demolished and replaced within a 14 day time frame.

The UHPC will be used in some critical bridge connection details, including a moment-resisting joint between deck panels over a pier, which is a unique approach for using UHPC in bridge construction. The bridge design has been performed in cooperation with the Iowa DOT and will be constructed using ABC techniques. Because several important bridge joints will utilize UHPC in the demonstration bridge, laboratory testing will be conducted at ISU prior to bridge construction to assess UHPC material handling during construction, including strength and serviceability of the bridge joints. The application of UHPC in these bridge joints will provide important insight into the future applicability of UHPC in addressing bridge durability.

UHPC piling for bridge structures

ISU laboratories and Mahaska County, Iowa

Minimizing bridge foundation deterioration is a primary challenge that significantly increases bridge service life and reduces life-cycle maintenance costs. Traditional piles composed of steel and concrete are subjected to corrosion and deterioration. Additionally, when concrete piles are driven they may be subjected to crushing and cracking due to excessive compressive and tensile stresses. Steel piles can experience local buckling. Using precast, prestressed UHPC pile foundations may help achieve targeted service life, avoid drivability problems and ensure durability of future bridges.

An ongoing study supported by the IHRB focuses on the potential use of UHPC piles. The study's Phase I final report (IHRB TR-558, "Use of Ultra-High Performance Concrete in Geotechnical and Substructure Applications") was approved by the board in November 2008. Phase I developed a UHPC pile design concept, demonstrated the potential use of UHPC in geotechnical applications, and

evaluated the behavior of UHPC piles using large-scale tests and analytical procedures. Phase II (IHRB TR-615, "Connection Details and Field Implementation of UHPC Piles") focuses on a field testing program of the UHPC piles to compare the behavior of an UHPC pile to an equivalent steel H pile.

The properties of UHPC suggest that a significantly reduced section could be used for an UHPC pile compared to typical sections used for precast, prestressed concrete piles without sacrificing the load-carrying capacity of the section (**Table 1**). UHPC can also use a much higher level of prestressing due to its high-compressive strength, which increases the resistance of the pile to flexural and axial tension.

The tested UHPC pile cross section was designed using UHPC moment-curvature relationships based on stress-strain experimental test data from ISU's research, supplemented by research from others. The final dimensions of the tapered H-shaped UHPC pile section are compared with an HP steel pile 10 inches deep by 57 pounds per foot length (**Figure 9**).

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	UHPC	Concrete (12 x 12)	Steel (HP 10 x 57)
Area of prestressing steel (in ²)	1.53	0.61	N/A
Total cross-sectional area (in ²)	56.8	144	16.8
Moment of inertia (in ⁴)	795	1728	294
Weight (lb/ft)	61.1	150	57.2

Table 1 – Some comparative properties for UHPC, concrete and steel piles section

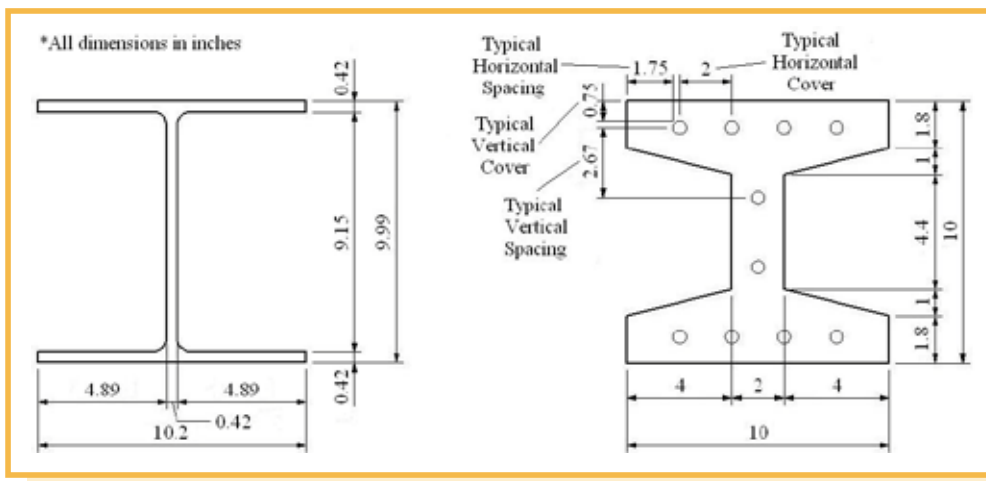


Figure 9 – Dimensions of an HP 10" x 57 lb. steel pile and a UHPC tapered H-shaped pile: notice the UHPC pile does not require ties or other shear reinforcement

Webinar from Google Maps and Enterprise GIS Partnership online!

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www.directionsmag.com/webinars/view/webinar-iowa-dot-takes-google-maps-into-enterprise-gis/153196

The UHPC pile units needed for use in laboratory and field tests in the Phase I study were prefabricated at Coreslab Structures Inc. near Omaha, Neb. (**Figure 10**).



Figure 10 – Layout of UHPC units for the first of two pours at Coreslab Structures Inc. near Omaha, Neb.

The laboratory tests on UHPC units were used to verify the structural behavior of the UHPC pile section under combined axial load and bending moment. Field tests on 35-foot UHPC piles proved the viability of producing, transporting and driving the piles. Vertical and lateral load behavior of driven UHPC piles were also examined. A total of five separate UHPC test units were cast: three small-scale test units were laboratory tested (two specimens were 8 feet long and had 3/4-scale section properties); one specimen was 10 feet long (with full-scale section properties); and two were full-scale test piles (35 feet long) for the field tests.

The laboratory tests under combined axial and lateral loads verified the moment-curvature behavior of the UHPC pile section designed for this study (**Figure 11**). Each test unit was fixed at the bottom end through a connection with the steel base. With this setup, the test unit experienced its maximum moment at the fixed connection with the base.



Figure 11 – Setup of UHPC test unit with a length of 10 feet and full-scale section properties; the tests allowed validation of the moment-curvature behavior of the UHPC pile



A UHPC pile driven at the test site: drivability characteristics were evaluated and the pile load tested

Two 35-foot-long UHPC piles were driven into the ground and load tested to verify their potential for application in bridge substructures (**Figure 12** and **Figure 13**). The UHPC piles were installed next to a bridge under construction near Oskaloosa. A HP steel pile 10 inches deep by 57 pounds per foot length was also installed and load tested so that it could be compared with the UHPC pile performance. Drivability characteristics and field performance of piles were evaluated.



Vertical load test of the steel pile at the Oskaloosa test site

Figure 12 – Field evaluation of UHPC and steel piles



Figure 13 – Testing of a full-scale beam and small-scale shear beams

This research should provide new and beneficial information to the bridge engineering community particularly interested in improving durability of bridge structure foundations. The study provides preliminary information regarding the viability of UHPC piles as an alternative to conventional prestressed concrete and steel piling. The high durability of UHPC is determined to provide lower maintenance and life-cycle costs than steel and concrete piles;

smaller groups of UHPC piles can be used because of the material's higher load capacity. Experience casting UHPC piles in a precasting plant has proven successful; and drivability testing of full-scale piles shows promise.

Phase II of this study is in progress to determine suitable splice details for the UHPC piles and the pile-to-pile cap connections details. Additional field tests and monitoring of a pile to be installed at a bridge site will be completed in this phase.

Based upon study results, the following are specific conclusions from Phase I.

- An optimized prestressed UHPC pile section without using any mild reinforcement was successfully designed. The 10" x 10" tapered H-shaped UHPC pile section achieved a weight approximately the same as that of a similarly sized HP steel pile 10 inches deep by 57 pounds per foot length, without significant reduction in moment capacity compared to the steel pile.
- UHPC piles can be successfully cast in a precasting plant as designed. High strengths of 26 - 29 ksi are achievable when the recommended heat treatment procedures for UHPC are followed.
- The laboratory test measurements confirmed that the theoretical approach followed for establishing the moment-curvature response of the UHPC pile section is satisfactory.
- Based on a driveability study in the field considering a wide range of materials, soils and driving hammers, it was concluded that driving stresses are well below allowable limits in UHPC piles in most conditions and the required pile cushion thickness for UHPC piles may be eliminated or reduced compared to those used in practice for HPC or normal concrete piles. Further, the study confirms that UHPC piles can be driven with the same driving equipment as steel piles of the same size and weight.

Waffle slab deck bridge *Wapello County*

To continue development of cost-effective bridge sections using UHPC, the FHWA investigated the potential of using UHPC waffle deck precast systems for bridges, creating a design procedure for a full-depth deck system in the process. After this development, other state DOTs expressed interest in UHPC components – particularly for use in replacement of existing deteriorated bridge decks.

A workshop sponsored by the Iowa DOT in cooperation with Wapello County and ISU was held in July 2008. Attended by industry, academia and FHWA personnel, the workshop (titled, "Design Concepts for Precast Waffle Slab Bridge Decks"), provided opportunity for discussion on the potential use of a UHPC waffle slab in a demonstration bridge. Subsequently, through FHWA's Highways for LIFE program funding and financial support from the IHRB, a field demonstration project (Little Cedar Creek bridge in Wapello County) was initiated, including laboratory and field testing and evaluation (IHRB TR-614) in October 2009. The Iowa DOT designed the bridge and laboratory test specimens (fabricated at Coreslab Structures Inc. in Omaha, Neb.). ISU is responsible for testing and evaluation.

Construction of the Little Cedar Creek Bridge is scheduled for spring 2011, with completion anticipated later in the year. The bridge will be 60 feet long and 33 feet 2 inches wide, and supported on five standard Iowa Type B prestressed girders spaced 7 feet 4 inches apart. The waffle slab was designed to be composite with the girders and is 8 inches in depth; mild reinforcement (nonprestressed) was used in the slab.

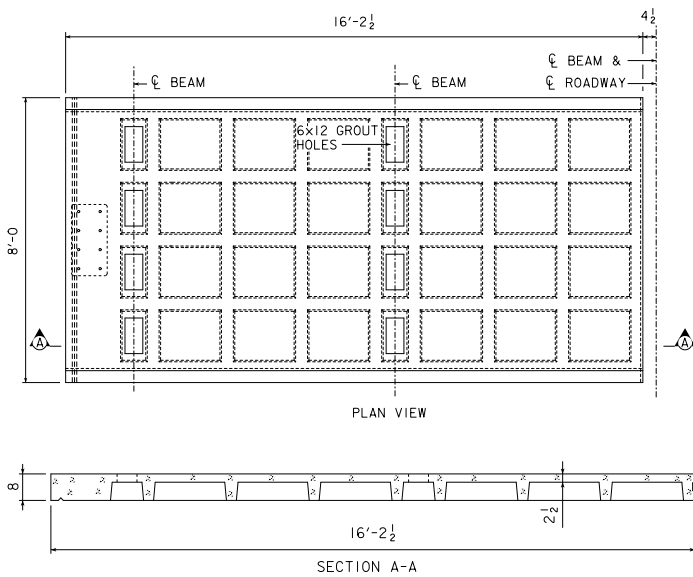


Figure 14 – Several views showing the geometry of the waffle slab for the Wapello County bridge

The bridge deck cross section is made up of two panels that are placed side-by-side in the transverse direction. Each panel is 8 feet long (measured along the bridge center line) and 16 feet 2.5 inches wide. (Figure 14) The waffle deck design was based on a modified empirical method, that was verified through laboratory testing during design.

The laboratory test specimens were designed to allow service, strength and fatigue testing of the deck panel; and several connection details between two adjacent decks panels, and between deck panels and the girders were tested (Figure 15).

Figure 15 – Design layout of a single deck panel for laboratory testing

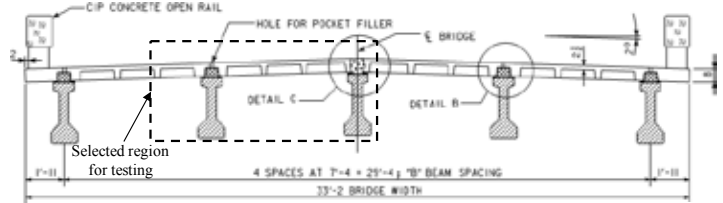
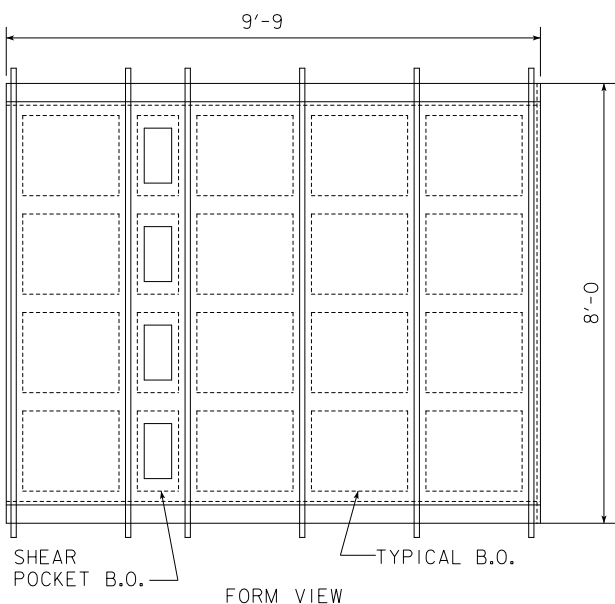


Figure 16 – Wapello County bridge cross section simulated for laboratory testing

The length dimensions of the test panels were the same as those for the Little Cedar Creek bridge: two panels (8 feet long by 9 feet 9 inches wide placed end to end) were pre-fabricated to span across two adjacent girders (Figures 16 and 17). The two prestressed girders supporting the deck slabs were 24 feet long.



UHPC placement of test panel form at Coreslab Structures Inc., Omaha, Neb.



Waffle slab placement for laboratory testing after shipment from Coreslab Structures Inc.

Figure 17 - Two laboratory specimens representing full-scale portions of the Wapello County bridge deck

UHPC hybrid bridge deck evaluation

Bridge deck cracking is a common problem in the United States. The deterioration of bridge decks is a leading cause for functionally obsolete or structurally deficient inspection ratings of bridges. Exposure of bridge deck steel to a combination of moisture, temperature and chlorides from deicing salts through surface cracks leads to concrete deterioration and loss of serviceability. Nationwide, billions of dollars have been spent replacing bridge decks deteriorated by the effects of cracking. Federal, state and municipal bridge engineers are seeking alternative ways to build better bridges, reduce travel times and improve repair techniques to reduce maintenance costs. Additionally, owners are challenged with replacing critical bridge components, particularly bridge decks, during limited or overnight road closures. Therefore, there is a need to develop and implement longer-lasting bridge deck systems that may use advanced materials, innovative technologies and safe, fast construction practices resulting in high-quality bridges and highways.

Some of the most important attributes of UHPC are high compressive strength, dependable tensile strength and low permeability when compared to normal concrete (NC) used in today's bridge decks. This helps control commonly seen deck cracking. Therefore, UHPC is gaining significant interest within the bridge engineering community for applications that increase longevity and reduce maintenance costs. The recent ISU study has shown excellent structural characteristics for a full-depth, precast waffle deck system for bridge applications.

The cost of UHPC material is significantly higher than normal strength concrete; this may hinder the routine use of UHPC in bridge decks. Because deck deterioration occurs when cracks form on the top surface, a very cost-effective, yet highly durable bridge deck could be produced by overlaying a thin UHPC layer on a NC slab, creating a composite bridge deck. However, a dependable shear friction for the UHPC and NC interface, and the factors influencing its behavior, needs to be investigated to make this concept a reality for field applications.

The Iowa DOT has initiated a research project focusing on the structural characterization of different shear-friction interfaces for overlying UHPC on NC slabs and identifying the most suitable interface for this connection. With due consideration to constructability, and benefits of strength and durability characteristics of heat-treated UHPC, the project will also address the factors influencing shear-fric-

The laboratory specimen was loaded as a single point load representing a wheel load at various critical locations on the deck panel (**Figure 18**). Critical locations were based upon finite element analysis of the specimen. The laboratory testing results of the UHPC waffle deck system indicated that the waffle deck performed satisfactorily, including the UHPC joint systems. No fatigue damage was noted during the testing; and displacements of the bridge deck were considerably smaller than American Association of State Highway and Transportation Officials allowable limits. Further testing and analysis of the transverse negative moment regions is recommended.



Figure 18 - Load testing of the waffle slab at ISU's Structural Engineering Laboratory; deck panel service, fatigue and strength level tests were performed; a similar series of tests were also performed to assess the panel-to-panel transverse joint performance

Through this study multiple organizations learned about design, construction, handling, fabrication and structural performance. After the Little Cedar Creek bridge is constructed, field testing and evaluation will be performed to provide further information about various aspects associated with bridges. Field data, combined with previously obtained laboratory testing data, will provide important information for potential use of these deck types in future design, construction and fabrication modifications, if needed. Given the potential durability benefits of UHPC, this waffle slab concept offers several potential benefits, including a viable precast deck alternative for use in ABC of new bridges and a precast deck alternative for use in replacing deteriorated decks on existing bridges.



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tion behavior, proposing a possible UHPC-NC composite deck system (**Figure 19**).

The broad objective of this work is to characterize shear-friction behavior between UHPC and NC surfaces, establishing suitable details needed to realize a UHPC-NC composite deck system. The proposed research will also evaluate the practicality and effects of different textures of surface preparations, concrete strength and precast/prestressed operations on shear-friction behavior of the composite deck (**Figure 20**).

This research has several benefits to bridge infrastructure in Iowa and nationwide. First, the study will lead to a durable UHPC-NC composite system that currently does not exist. Second, by combining UHPC and NC, the research will minimize the use of UHPC, reducing the initial construction costs by as much as 50 percent compared to use of waffle decks made entirely of UHPC. Third, the composite section also allows for use of the new concept to existing bridge decks, reducing the number of bridges with deteriorated decks. With such broad applications of UHPC and NC composite deck, this study will ultimately reduce both construction and maintenance costs of bridge decks.

Conclusions

The Iowa DOT's capacity to advance implementation of cost-effective, safe and durable bridge materials, methods and design requires staying on the leading-edge of technology. This is typically accomplished through involvement with national technical committees, interaction with other state DOTs and federal transportation agencies, and participation in technology transfer opportunities and research.

To effectively implement advanced materials into bridge design, construction and maintenance, it is imperative that bridge engineers be directly engaged in research opportunities to better understand materials and methods interactions. Research and demonstration projects like those described within provide those involved opportunities. Through these types of activities, the Iowa DOT has gained a much better understanding of how UHPC may prove useful in future projects. Continuation of research and demonstration bridge projects will be a priority for advancement of bridge technologies.

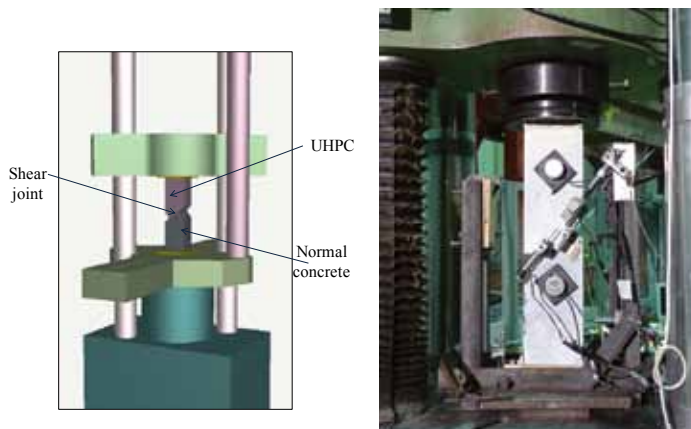


Figure 19 – Setup used for UHPC- NC shear-friction interface testing

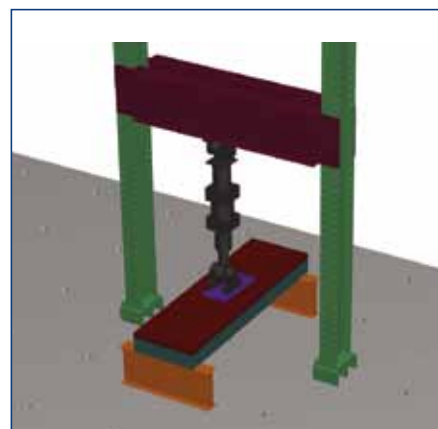


Figure 20 – Proposed test setup for laboratory testing of composite deck

About the authors



Dr. Terry Wipf achieved his Ph.D. in mechanics and energetics engineering from the University of Nebraska-Lincoln. He is currently the director of ISU's Bridge Engineering Center, and a division leader and professor in the department of civil, construction and environmental engineering.



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UHPC Pi-Girder Bridge Project Highlighted

Iowa Highway Research Board (IHRB) project **TR-574, "Design, Construction, and Field Testing of an Ultra-High Performance Concrete Pi-Girder Bridge"** conducted by ISU Bridge Engineering Center Director Terry Wipf, was approved by the Board at February's meeting and is highlighted on the Iowa DOT Research Bureau [Operations Research homepage](#) and in the March 8, 2011 edition of the [TRB E-Newsletter](#).

The 90th Annual TRB Meeting DVD Compendium is online

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