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Structural Characterization of UHPC Waffle Bridge Deck and Connections

Abstract

The AASHTO strategic plan in 2005 for bridge engineering identified extending the service life of bridges and accelerating bridge construction as two of the grand challenges in bridge engineering. These challenges have the objective of producing safer and more economical bridges at a faster rate with a minimum service life of 75 years and reduced maintenance cost to serve the country's infrastructure needs. Previous studies have shown that a prefabricated full-depth precast concrete deck system is an innovative technique that accelerates the rehabilitation process of a bridge deck, extending its service life with reduced user delays and community disruptions and lowering its life-cycle costs. Previous use of ultra-high performance concrete (UHPC) for bridge applications in the United States has been considered to be efficient and economical because of its superior structural characteristics and durability properties. Full-depth UHPC waffle deck panel systems have been developed over the past three years in Europe and the United States. Subsequently, a single span, 60-ft long and 33-ft wide prototype bridge with full-depth prefabricated UHPC waffle deck panels has been designed and built for a replacement bridge in Wapello County, Iowa. The structural performance characteristics and the constructability of the UHPC waffle deck system and its critical connections were studied through an experimental program at the structural laboratory of Iowa State University (ISU). Two prefabricated full-depth UHPC waffle deck (8 feet by 9 feet 9 inches by 8 inches) panels were connected to 24-ft long precast girders, and the system was tested under service, fatigue, overload, and ultimate loads. Three months after the completion of the bridge with waffle deck system, it was load tested under live loads in February 2012. The measured strain and deflection values were within the acceptable limits, validating the structural performance of the bridge deck. Based on the laboratory test results, observations, field testing of the prototype bridge, and experience gained from the sequence of construction events such as panel fabrication and casting of transverse and longitudinal joints, a prefabricated UHPC waffle deck system is found to be a viable option to achieve the goals of the AASHTO strategic plan.

Keywords

Bridge construction, Bridge decks, Load tests, Precast concrete, Ultra high performance concrete, Wapello County (Iowa), Accelerated bridge construction, Bridge deck connections, Highways for LIFE, Waffle deck

Disciplines

Civil Engineering

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Structural Characterization of UHPC Waffle Bridge Deck and Connections

tech transfer summary

A precast UHPC waffle deck with enhanced durability properties is shown to be an effective alternative to a routinely used concrete bridge deck needing frequent maintenance.

July 2014

RESEARCH PROJECT TITLE
Structural Characterization of UHPC Waffle Bridge Deck and Connections

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IOWA STATE UNIVERSITY
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Research Objectives

- Contribute to design an innovative and durable precast deck alternative using ultra-high performance concrete (UHPC) for accelerated bridge construction
- Evaluate the structural characteristics of the UHPC waffle deck, critical connections, and system performance using large-scale tests for implementation in a replacement bridge in Wapello County, Iowa
- Perform live load testing of the Wapello County, Iowa Bridge with waffle deck panels to validate the expected performance of the waffle deck panel system under moving loads

Problem Statement

Today there are more than 147,000 bridges in the United States that are structurally deficient or obsolete, with more bridges added to this list each year. Deterioration of the bridge decks is a leading cause for the obsolete and/or deficient inspection ratings of the bridges. The Departments of Transportation (DOTs) are challenged with replacing critical bridge components, particularly rapidly deteriorating bridge decks, during limited or overnight road closure periods.

To address this issue, a recent analytical study by the Federal Highway Administration developed a durable, prefabricated full-depth waffle deck system concept using UHPC. However, there were no experimental studies completed to characterize the system performance and constructability. Therefore, large-scale testing of the UHPC waffle deck concept was needed prior to deploying this new bridge deck in the field.

Research Methodology

The research methodology for this project included full-scale laboratory testing followed by live load testing of a completed full-scale bridge and the work was completed in two phases. In Phase I, design and large-scale testing of a mock-up bridge section with connections was performed for verification of design assumptions, as well as verification of the feasibility of manufacturing and installation of the deck elements. In Phase II, construction process monitoring and live load performance evaluation of the completed demonstration bridge were completed in Wapello County.

Design

A full-depth UHPC waffle deck panel was designed by the Office of Bridges and Structures of the Iowa DOT in collaboration with Coreslab Structures (OMAHA) Inc., Iowa State University, and Wapello County for a single-span, 60 ft long and 33 ft wide bridge as a replacement for an existing bridge in Wapello County.

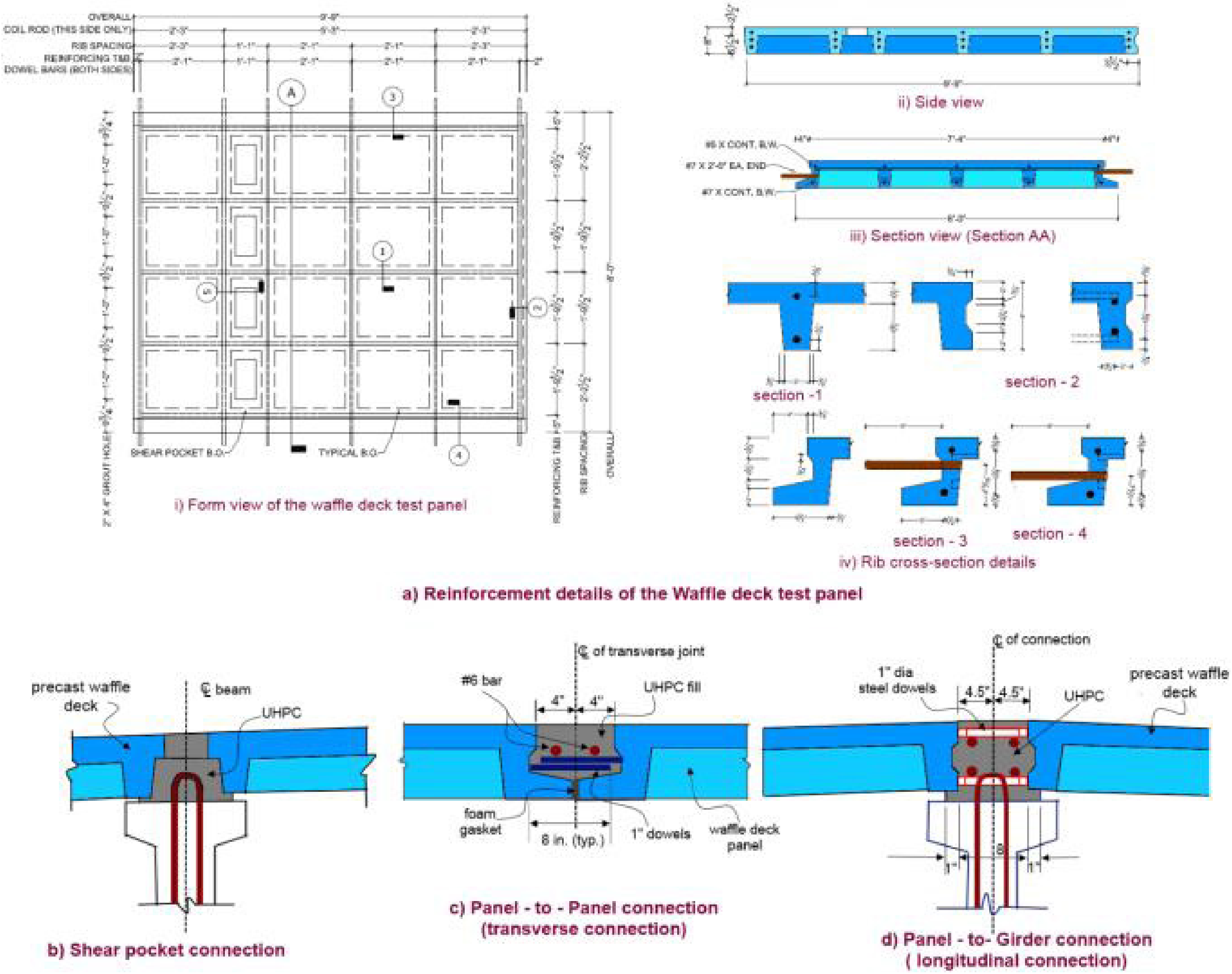


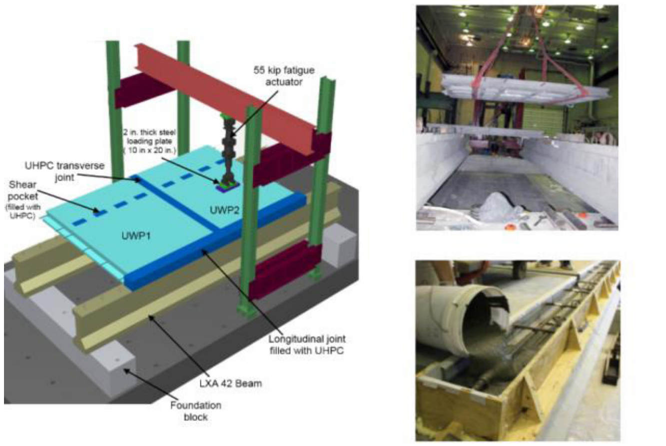
Figure 1. Design and connection details of the UHPC waffle deck system

- The UHPC waffle deck panel was 8 inches thick and consisted of a 2.5-inch thick slab cast integrally with 5.5 inch deep concrete ribs spanning in transverse and longitudinal directions.
- The waffle deck panel was designed according to the current guidelines of the American Association of State Highway and Transportation Officials (AASHTO). This resulted in grade 60, No. 7 (d_b = 0.875 inch, where d_b = diameter of the reinforcement) and No. 6 (d_b = 0.75 inch) bars as bottom and top reinforcement, respectively, placed along both the transverse and longitudinal ribs (see Figure 1a).
- The waffle deck panel system was designed to act fully composite with the prestressed concrete girders using three different connections, namely, shear pocket connection at the girder locations (see Figure 1b); panel-to-panel transverse connection, located between the panels (see Figure 1c); and panel-to-girder longitudinal connection (see Figure 1d) at the girder located at the center of the bridge cross section.

Laboratory Testing

Prior to field implementation, the structural performance characteristics and the constructability of the UHPC waffle deck system and its critical connections were studied through large-scale laboratory testing at the structural laboratory of Iowa State University.

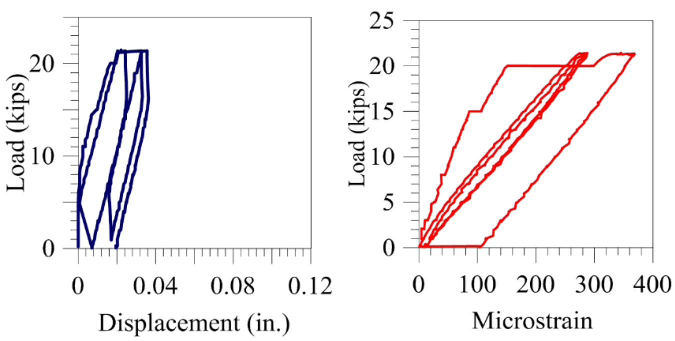
- The test specimen (see Figure 2) consisted of two prefabricated full-depth UHPC waffle deck (8 foot by 9 foot 9 inches by 8 inches) panels, connected to 24-foot long precast girders (Iowa standard LXA 42 girder) using cast-in-place connections with field cast UHPC (see Figure 2). This test setup closely replicated the critical regions of the field structure in the laboratory.
- The two test waffle deck panels were fabricated by Coreslab using commercially available standard Ductal mix and special forms designed for this project. The test panels were cast in an upside position using a displacement method, to facilitate a flat finish for the driving surface and easy placement and removal of the voids.



a) Schematic of laboratory test setup

b) Placement of deck panels and pouring of UHPC in joints

Figure 2. Laboratory test specimen construction and setup



a) Panel displacement under load location

b) Measured strain in the bottom panel transverse reinforcement

Figure 3. Waffle deck panel response under service load of 21.3 kips

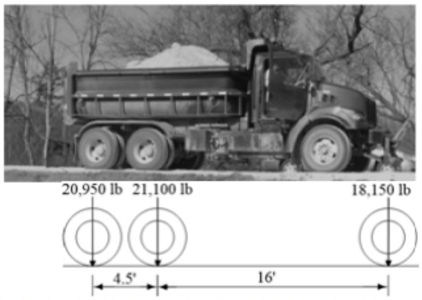
- The performance of the UHPC waffle deck system, including the UHPC joints, was examined using nine different tests (see Table 1) and a single wheel truck load placed at the center of the deck panel and center of the transverse joint between the deck panels. A large number of instrumentations, including string pots and strain gages, were used to measure critical parameters.
- Under the maximum service load of 21.3 kips, measured deflection and critical tensile strains in the bottom transverse reinforcement of the waffle deck panel were 0.03 inch and 0.000375 inch/inch, respectively (see Figure 3). These measured deflection values are around 18% of the specified AASHTO serviceability limits. A single hairline crack (width < 0.002 inch) was observed at the center of the transverse rib under the load.
- A maximum deflection of 0.022 inch and a maximum strain of 0.000170 inch/inch were measured when a service level load of 28 kips was applied at the center of the transverse joint. The measured deflection values is 20% of the allowable limit, whereas the measured strain is 8% of the yield value.
- Both the panel and the transverse joint were subjected to 1,000,000 service level load cycles. Neither the UHPC waffle panel nor the UHPC joints experienced any fatigue damage under service loads.
- At ultimate loads, the deck panel and transverse joints experienced significant cracking. The measured maximum strains in transverse reinforcement were within 76% of the yield value. The bottom No. 7 reinforcement can be changed to No. 6 reinforcement to simplify the construction without having an effect on design capacity.
- The panel experienced a sudden punching shear failure at a maximum load of 155 kips, using a 6 inch by 8 inch plate between the ribs. The measured average punching strength is 1.068 ksi, which is significantly higher than the previously measured value in the literature.
- Punching failure is not expected under standard wheel load.

Table 1. Sequence and details of the tests conducted on the waffle deck system

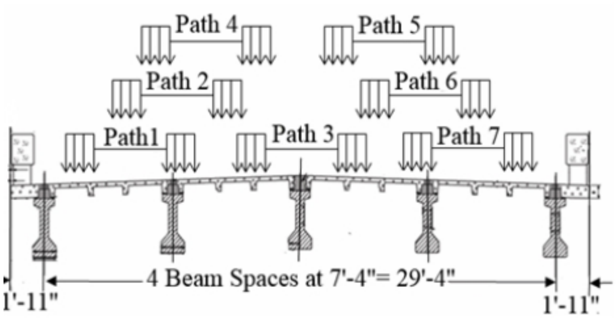
Test	Test Description	Location	Maximum Load (kips)	Expected Damage
1	Service load test panel-2 (UWP2)	C.O.P	1.33^a x 16 k = 21.3 k	Micro cracking in ribs
2	Service load test on transverse joint	C.O.J	1.75^b x 16 k = 28 k	Micro cracking in joint
3	Fatigue test on transverse joint	C.O.J	28 k (1 Million cycles)	No prediction was made
4	Overload test of transverse joint	C.O.J	48 k	Visible flexural cracks along the joint and transverse ribs
5	Fatigue test on panel-1 (UWP1)	C.O.P	21.3 k (1 million cycles)	No prediction was made
6	Overload test of panel	C.O.P	40 k	Several visible flexural cracks along transverse ribs
7	Ultimate load test on panel UWP1	C.O.P	160 k	Significant cracking
8	Ultimate load test on transverse joint	C.O.P	155 k	Significant cracking
9	Punching shear failure test on UWP1	Between trans-verse ribs	155 k	Punching shear failure

a, b—dynamic load allowance factors from AASHTO Table 3.6.2.1-1

C.O.P—center of the panel; C.O.J—center of the joint



a) Dump truck used for live load testing



b) Load paths used for live load testing

Figure 4. Live load testing of the Wapello County Bridge

Field Construction and Live Load Testing

Following the successful laboratory testing, a demonstration bridge on Dahlonega Road in Wapello County was constructed using prefabricated UHPC waffle deck panels. Based on the experimental investigation, No. 6 reinforcement was used for both top and bottom deck reinforcement in transverse and longitudinal directions. The 16 ft 2.5 inch long and 8 foot wide UHPC waffle deck panels were cast at the precast plant (Coreslab) and placed on the girders during the week of September 12, 2011. The deck joints were casted using field cast UHPC during the last week of September, and the bridge was open to traffic in November 2011. Field testing of the bridge was performed in February 2012 using a standard dump truck weighing 60,200 pounds (Figure 4). As shown in Figure 4, seven load paths—including two load paths at 2 feet from the barrier rails, load paths at the centerline of traffic lanes, 2 feet offset from the centerline of the bridge, and a load path straddling the centerline of the bridge—were used to evaluate the live load performance.

Key Findings

- None of the strain gages spanning the interface between prefabricated deck panels and their adjacent UHPC infill joints indicated opening of the interface.
- Preexisting flexural cracks on the bottom ribs of the UHPC waffle slab panel adjacent to the abutment were observed prior to live load testing. Finite element analysis indicated that these cracks were likely caused during storage, shipping, or erection rather than due to vehicular loads.
- Only two strain gages on the deck panels adjacent to the abutment registered strains greater than the expected cracking strain of the UHPC. Because these strains were not excessive (i.e., less than those measured at service load levels during laboratory testing) and were located on the underside of the deck, no negative impacts to the performance and durability are expected for the waffle deck panels.
- The maximum live load distribution factor for the interior girder was computed to be 0.51, which is lower than the AASHTO-recommended value of 0.63.
- The maximum dynamic amplification factor for the bridge girders was computed to be nearly 1.4, which is close to the AASHTO-recommended value of 1.33.

Implementation Benefits

The use of a prefabricated UHPC waffle deck system in the Wapello County Bridge was a first for the United States and is one of many concepts being employed to reduce road closure time as part of the development of Accelerated Bridge Construction practices to be used throughout the country. The reduced weight and improved durability of the deck panel compared to the traditional precast concrete full-depth panel will increase the longevity and help in decreasing the maintenance. The simple deck panel connections developed and tested as part of this project can be used in conjunction with a traditional full-depth precast deck panel to minimize the joint widths, improving the durability of the joints. A design guide (Aaleti et al. 2013) developed based on analytical studies, supported by the experimental data from this project, also helps in usage of the waffle deck panel in a variety of new and existing bridges.

Recommendations for Further Research

- In this completed prototype bridge, the UHPC waffle deck panel was used in a single span, straight simply supported bridge. For a broader use of this concept, the applicability of the current concept and the connection details for curved and skewed bridges needs to be investigated.
- The performance of connections and deck panels at the pier location in a continuous bridge needs to be investigated.
- Given the low strain demand, it may be possible to optimize the rib spacing to make the waffle deck system more economical.

Reference

Aaleti, S., B. Peterson, and S. Sritharan. 2013. *Design Guide for Precast UHPC Waffle Deck Panel System, Including Connections*. Report No. FHWA-HIF-13-032. Washington, DC: Federal Highway Administration. www.fhwa.dot.gov/hfl/pubs/hif13032/hif13032.pdf