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RESEARCH PROJECT TITLE
Design, Construction, and Field Testing of an Ultra-High Performance Concrete Pi-Girder Bridge

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The Bridge Engineering Center (BEC) is part of the Institute for Transportation (InTrans) at Iowa State University. The mission of the BEC is to conduct research on bridge technologies to help bridge designers/owners design, build, and maintain long-lasting bridges.

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Design, Construction, and Field Testing of an Ultra-High Performance Concrete Pi-Girder Bridge

tech transfer summary

Unique ultra-high performance concrete (UHPC) pi-girders demonstrate a new and effective option for bridge superstructures, especially for projects with accelerated construction schedules.

Introduction

North America has increased interest in and research into the use of ultra-high performance concrete (UHPC) for bridge superstructures. By using UHPC, departments of transportation hope to gain significant advantages in the mechanical properties and durability of concrete. Tradeoffs of using UHPC include increased cost of materials, increased batch time for mixes, modification of forms due to increased shrinkage, and long setting and curing times that occupy precast beds.

The Jakway Park Bridge in Buchanan County, Iowa is the first bridge in the US constructed with a second-generation pre-stressed girder system composed of precast UHPC. The girders have a unique cross section named for their resemblance to the Greek letter π.

Background

In 2008, the Iowa Department of Transportation (DOT) and the Federal Highway Administration (FHWA) took the initiative to design and build a UHPC pi-girder demonstration bridge. Funding for the project was awarded to the Iowa DOT through the FHWA Innovative Bridge Research and Construction Program (IBRC). The Bridge Engineering Center (BEC) at Iowa State University (ISU) was funded by the Iowa Highway Research Board (IHRB) to assist with the bridge design, document the bridge construction, and evaluate the structural performance of the bridge.

Constructed in the Fall of 2008, the Jakway Park Bridge in Buchanan County, Iowa was the first North American highway bridge constructed using innovative pi-girders cast of UHPC. The pi-girders were cast with an integral deck and enhanced wearing surface durability.

The Jakway Park Bridge in Buchanan County, Iowa demonstrates the effectiveness of innovative design, materials, and construction techniques for new bridge structures

A first-generation pi-girder shape was developed for research at the Massachusetts Institute of Technology (MIT). The shape was established to optimize the economy of the section while maintaining sufficient strength. FHWA testing of the first-generation pi-section raised concerns over lateral load distribution and the possibility of crack formation in the thin deck under American Association of State and Highway Transportation Officials (AASHTO) design loads.

Second-Generation Bridge Design

The second-generation pi-girder introduced larger section properties. Using finite element analysis, the bridge design was conceived and completed by the Office of Bridges and Structures at the Iowa DOT.

Construction

Construction of the Jakway Park Bridge was conducted throughout the Fall of 2008. The total construction time was 52 days, and the bridge was opened to traffic on November 26, 2008.

Objectives

- Ensure adequate performance of this first-of-its-kind design
- Quantify conservatism in the design approach
- Provide guidance to inform future bridge designs using UHPC pi-girders

Scope

The primary objectives of this investigation were to quantify the local and global behavior of the bridge and to provide guidance for future designs employing UHPC pi-girders. Through construction monitoring and live load testing, the conservatism of the design approach was quantified and specific parameters, such as lateral live load distribution factors, dynamic amplification factors, and maximum span length, were determined.

Construction using the second-generation pi-girders (cast with an integral deck and enhanced wear surface durability)

To complete the overall objectives, the project included the following tasks:

- Documentation of bridge design process
- Strain monitoring during diaphragm installation
- Completion of two live load field tests considering both static and dynamic loads
- Completion of laboratory tests of UHPC cylinder and beam specimens cast from material used in the pi-girders
- Verification of the analytical approach used in design by comparison of field tests to predicted analytical results

This project documents the evolution of the pi-girder geometry, design and analysis of the bridge, and testing performed to evaluate performance of the bridge. The report documents the evolution of the pi-section from first to second generation, the design assumptions and approach, the analytical techniques used in design, and the construction of the bridge.

The results of laboratory testing, construction monitoring, and live load field testing are presented to quantify the local and global behavior of the Jakway Park Bridge to provide guidance to future designs that employ UHPC pi-girders.

Research Description

To accomplish the objectives, laboratory testing on UHPC materials, construction monitoring during diaphragm installation, and two live load field tests were performed.

Laboratory Testing

Laboratory testing involved concrete material tests for compressive and flexural strength. Specimens cast at the LaFarge plant in Winnipeg, Canada were sent to ISU for testing. The test samples were cast alongside the girder in September 2008 and tested in May and October 2009.

Research team instrumented the bridge for two sets of field tests, which were conducted nearly a year apart

Field Testing

Field testing of the Jakway Park Bridge took place in both November 2008 and September 2009. The tests were conducted roughly a year apart to observe any possible changes in the behavior of the bridge throughout the first year of service. Through field testing, this investigation was able to quantify the response of the bridge under service level loads and subsequently quantify the conservatism present in the design.

Key Findings

As of the second live load field test in September of 2009, the bridge appeared to be performing well and within the general design parameters. Strains measured during live load testing at critical locations of the bridge indicated that cracking is unlikely at service level loading.

However, testing identified several parameters that could be less conservative in future designs thus yielding cost savings. Chief among these parameters are longer spans (up to 65 ft from 50 ft with the girders used in this bridge while still avoiding cracking of the UHPC), lower live load distribution factors (25% reduction for the girder configuration and connections used in this bridge), and elimination of all mild steel reinforcing. While still costly in comparison with more-conventional bridge designs, the UHPC pi-girders should likely become more cost competitive as life-cycle cost data are accumulated and design processes become more streamlined.

The maximum tensile strains computed in the UHPC pi-girders for this bridge were located in the webs and oriented vertically. This effect is due primarily to significant residual strains induced during installation of steel diaphragms with imperfect fit. Special consideration should be given to specified construction tolerances allowed for these members relative to the in-place geometry of the pi-girders. Total tensile strains measured in these areas, however, were still well below the cracking threshold.

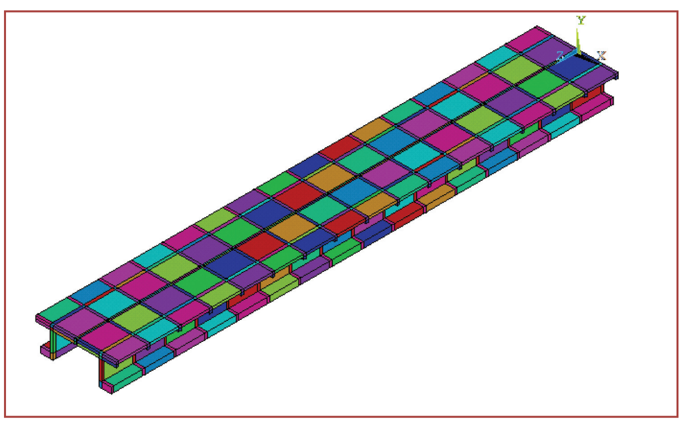
The laboratory and live load testing as well as analytical work regarding finite element model verification resulted in the formulation of the following findings and conclusions:

Design Assumptions and Future Design Guidance

- The pi-girders have lateral distribution factors ranging from 0.62 for exterior girders and 0.75 for interior girders. The design value of 1.0 was, therefore, conservative.
- The bridge did not behave as if perfectly simply supported as assumed in design. The concrete diaphragms at the piers appear to have provided some degree of continuity between the end spans and pi-girder span. However, the 2009 test showed that the UHPC centerspan appeared to have lost some degree of rotational restraint.
- The Interim 2008 AASHTO case (i), Precast Double T Beam equations for distribution factors, predicted reasonable and somewhat conservative estimates of distribution factors for this UHPC pi-girder bridge.
- Based on the measured live load strains and allowing for a 2 in. (5 cm) asphalt overlay and an impact factor of 1.33, the girder length could be increased to roughly 65 ft (20 meters) without cracking for Interim 2008 AASHTO specified loads.
- Construction strains induced by tightening of the hollow structural section (HSS) members are significant in the webs—often of similar magnitude to the strains recorded during live load tests. Tighter fabrication tolerances for diaphragm members may be appropriate.
- The maximum measured dynamic amplification factor was 1.15 for speeds up to 25 mph. The specified AASHTO dynamic amplification factor of 1.33 is conservative for this bridge.
- The steel diaphragms are not overly effective in improving the live load distribution between pi-girders for service level loads. However, when the midspan diaphragm was active, the maximum live load strains on the bulbs were reduced by roughly 6%.
- The steel diaphragm at midspan is not effective in decreasing the vertical web strain.

Finite Element Model (FEM)

- The simplified, linear-elastic FEM provided accurate means of predicting values of live load strains and deflections, and thus distribution factors for this UHPC pi-girder bridge.
- The distribution factors predicted by the FEM model matched to within 8% of the actual distribution factors measured in the field.
- The simplified method of modeling pre-stressing strands as pressures distributed over the bulbs of the pi-girder provided accurate estimates for both strain and deflection.
- Some improvement in predictions with relatively little additional cost might be achieved by employing elastic rather than coupled connections between each girder.



Finite element model (FEM) of single pi-girder for the bridge

Maximum Bridge Strains

- The estimated total longitudinal strain for the bottom of the bulbs at midspan and quarterspan were always compressive during testing and approximately 265-325 microstrain (με) below the cracking threshold, indicating that transverse cracking is unlikely at service level loads.
- The estimated total transverse strain on the bottom of deck were roughly 80 με below the cracking threshold, indicating that longitudinal cracking on the bottom of the deck is unlikely at service level loads.
- The estimated total longitudinal straisn for the top of the deck were roughly 155 με below the cracking threshold, indicating that transverse cracking is unlikely at service level loads.
- The estimated total vertical strains for the webs at midspan including residual strains from diaphragm installation were 30 με below the cracking threshold, indicating that horizontal cracking of the webs is unlikely at service level loads.
- The estimated total vertical strains for the webs at three-eighths span including residual strains from diaphragm installation were 50 με below the cracking threshold, indicating that horizontal cracking of the webs is unlikely at service level loads.

Comparison of 2008 and 2009 Static Live Load Tests

- In general, the changes in strain observed for the comparison of the 2008 to 2009 static live load tests were minimal.
- No significant change in the neutral axis location was observed. The 2008 neutral axis was 11.6 in. and the 2009 the neutral axis was measured to be 11.8 in. from the top from the section.
- The largest increase in strain was observed on longitudinal gages, where a loss of rotational restraint at the pier appeared to have caused a slight increase in strain. Thus, after a year of service, the bridge was behaving more nearly as designed.

Load testing the bridge was part of the structural performance evaluation

Implementation Benefits

The unique UHPC pi-girders used in the construction of the Jakway Park Bridge provide a new and effective option for bridge superstructures, particularly for projects with accelerated construction schedules. This bridge appears to be performing well and within the general design parameters. In addition, testing revealed that, over the first year of service, the bridge experienced only minor changes in structural behavior.

Implementation Readiness/ Recommendations

The design approach for the bridge was appropriately conservative considering the relatively new geometry and materials. Future applications of this technology may be less conservative. In particular, future designs could utilize longer spans, lower live load distribution factors, and most likely dispense with transverse mild steel reinforcement in the deck portion of the girders.

From the recommendations provided through this study and the continued decrease in cost of UHPC and fiber reinforcement in North America, UHPC pi-girder bridges will become a more cost-effective option.

If cracking of the UHPC is used as a criterion to limit stresses for durability considerations, relatively simple, linear-elastic FEMs can provide a highly useful tool in predicting behavior of the UHPC pi-girders. Such models can be developed cost-effectively and provide a useful tool for designers in predicting behavior, anticipating locations of concern, evaluating details, and identifying global changes in bridge performance through subsequent load tests. The verification of these models is of particular significance for future designs employing the distinctive UHPC pi-girder.

Potential Future Research Topics

- Use of partial pre-stressing in UHPC pi-girder design (i.e. cracking of UHPC on the bottom of the bulbs is allowed under maximum service level loads) could yield cost savings. The unhydrated cement content of UHPC would provide for second hydration thus providing crack-sealing capabilities.
- Investigation of the torsional properties of the 2nd-generation pi-section and the section's ability to resist eccentric loading should be more closely examined especially for longer spans.
- Life cycle costs of the pi-girder compared to traditional pre-stressed concrete beams should be quantified.