DESIGN GUIDANCE FOR UHPC CONNECTIONS OF PRECAST GIRDERS MADE CONTINOUS FOR LIVE LOAD

Quarterly Progress Report
For the period ending November 30, 2022

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1. Background and Introduction

Ultra-high performance concrete (UHPC) is a relatively recent advancement in cementitious composite materials with mechanical and durability properties which far exceed those of conventional concrete and which has potential for multiple applications in accelerated bridge construction (ABC). One such application is connection of precast, prestressed concrete bridge girders to make spans continuous for live load. Use of these continuity connections allows for construction of bridges using precast elements while also allowing for structural benefits of live load continuity and durability benefits of reducing the number of bridge deck joints. While design of conventional concrete continuity joints is well known and frequently used in practice for new construction, little guidance exists on design of these connections using UHPC or using UHPC to retrofit simple span bridges for live load continuity. UHPC has high tensile strength, excellent bond strength to substrate concrete, and short required development length for steel reinforcement making it an ideal material for these continuity connections. The current project extends previous research by the PIs on structural behavior of UHPC continuity connections to produce design guidance. Information and data from the literature will be synthesized with current design practice to extend design guidance beyond the limitations of the PIs' previous work. The primary output of the project will be the Guide for Design of UHPC Continuity Connections, but educational materials and design examples will also be produced as part of the project.

2. Problem Statement

Use of continuous bridge spans can reduce the required section size or increase capacity for a given size structural element. However, accelerated bridge construction (ABC) typically relies on precast components that can be quickly assembled on site. Establishing continuity for precast elements leads to resistance of live loads beyond the self-weight of the girders. Eliminating interior joints by establishing continuity can improve the durability, appearance, and riding quality of the bridge in addition to reducing maintenance costs (Freyermuth 1969). Some research (Oesterle et al. 1989) has disputed the effectiveness of full continuity connections, but in general the literature indicates that the connections do provide structural benefits and the system of precast beams made continuous for live load is used by multiple state DOTs.

Conventional connections of precast girders made continuous for live load consist of either individual linkage blocks placed between girder ends or continuity diaphragms extending the full width of the bridge. Tension from negative moment present over the pier is resisted in the connections by reinforcing steel placed in the bridge deck (Miller 2004). Prestressing strands and/or reinforcing steel are typically extended from the beam ends into the connections to provide positive moment resistance for restraint induced moments caused by creep and shrinkage of the bridge girders. If not detailed and constructed properly, conventional continuity connections tend to crack from the bottom due to moments resulting from creep and shrinkage effects (see Figure 1) (Saadeghvaziri et al. 2004, Miller 2004). This cracking has been shown to reduce the effectiveness of the continuity joint, leading to varying levels of continuity from fully continuous to behavior like that of a link slab (Saadeghvaziri et al. 2004, Miller 2004) which does not provide the benefits of full live load continuity and can lead to inadequate bridge capacity if the bridge spans are designed to be continuous. Some states have discontinued the use of this system due to cracking in the continuity connections. On the other hand, retrofitting a bridge originally designed as a series of simple spans to be continuous can increase the load carrying capacity. While age of the girders at the time of placement is a major consideration for performance of continuity joints due to the impact of creep and shrinkage (Saadeghvaziri et al. 2004), other factors such as cracking resistance of the joint material, reinforcement development length, and bond of the joint material to the girder concrete can be important considerations for design of continuity connections.

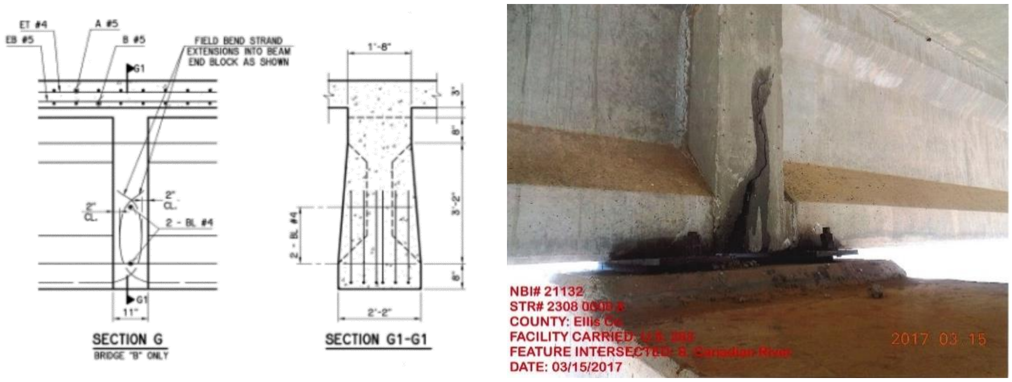


Figure 1. Detail for a typical continuity linkage block used in Oklahoma (left) and photo of a linkage block exhibiting cracking from restraint induced moments (right)

Ultra-high performance concrete (UHPC) is a relatively recent advancement in cementitious composite materials with mechanical and durability properties which far exceed those of conventional concrete. UHPC has been successfully used in multiple applications related to connection of precast concrete bridge components and is frequently used in ABC construction due to its superior bond development characteristics with steel reinforcement, ease of placement, and long-term durability compared to conventional concrete. In general, joints replaced or connections made using this material will have better durability, better resistance to impacts and abrasion, and will allow for a smaller quantity of material to be used while still obtaining adequate load transfer between connected components. Using UHPC allows for small, simple connections without the need for post-tensioning (when connecting precast elements) or large amounts of field-cast concrete (Graybeal 2010). Joints cast using UHPC also tend to behave more like monolithic construction than typical field-cast connections. The material characteristics, steel and concrete bond characteristics, flowability, and required quality control testing differ from conventional materials and require consideration in design for effective use of the material in precast girder continuity joints.

Extensive investigation of the properties of UHPC for use in bridge and other infrastructure components has been conducted by multiple organizations (e.g., Graybeal 2011, Graybeal 2014). The Federal Highway Administration (FHWA) defines UHPC as “a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement. According to the FHWA definition the mechanical properties of UHPC include compressive strength greater than 21.7 ksi (150 MPa) and sustained postcracking tensile strength greater than 0.72 ksi (5 MPa), however other definitions of UHPC class materials do not require the high compressive strength. Non-proprietary UHPC mixtures meeting all or some of the required characteristics have become more common in recent years. UHPC has excellent durability performance due to its discontinuous pore structure compared to conventional and high-performance concretes (Graybeal 2011). The post-cracking tensile strength is such that it can be included in design of structural elements and the steel fiber reinforcement can keep most cracks that form during normal service very small in width. Bond strength of mild steel reinforcement cast in UHPC (e.g. Graybeal 2010, Swenty and Graybeal 2012), bond strength of prestressing strand cast in UHPC (e.g. John et al. 2011, Graybeal 2006) and bond strength of UHPC to conventional concrete (e.g. Hussein et al. 2016, Carbonell et al. 2014, Tayeh et al. 2013) are superior to behavior of conventional concrete materials.

While the material characteristics of UHPC are very desirable for use in this application, limited research has been conducted specifically focused on examining the behavior of UHPC continuity joints. Previous research sponsored by ODOT (Casey 2019) and others (Rallabhandhi 2016) showed improvement in cracking resistance and overall behavior for UHPC connections of precast girders in high moment regions. Casey (2019) also indicated significant capacity increase for girder systems made continuous with UHPC retrofit connections. An implementation project using UHPC to replace existing linkage blocks that had cracked was completed in Oklahoma and is currently being monitored by the authors of this proposal. Pre-repair and post-repair load tests were conducted and the results indicate that continuity was effectively reestablished (Looney et al. 2021).

Previous research has shown that connections of precast girders for live load continuity using UHPC are a promising alternative to conventional connections for new construction and for retrofit solutions. Structural design and analysis of UHPC components can be accomplished using procedures similar to reinforced concrete if typical assumptions are modified to reflect the known structural behavior of UHPC. FHWA has published guidance on design and implementation of field-cast UHPC connections (Graybeal 2014). No design guidance is available specifically on using UHPC for live load continuity connections, however an in-progress project on UHPC connections in deck bulb-tee girder bridges sponsored by NCHRP (2018) has a partial focus on continuity connections. More comprehensive design guidance for continuity connections made with UHPC is needed for a variety of precast concrete bridge configurations.

3. Objectives and Research Approach

The objectives of the current project are to synthesize existing data and research on UHPC and UHPC connections to develop design guidance for UHPC connections of precast bridge girders made continuous for live load and to produce training materials for UHPC continuity joints.

The current project consists of evaluation and synthesis of existing test data and current design practice to develop design guidance for UHPC connections of precast concrete girders over a pier to create live load continuity. The existing provisions in the AASHTO LRFD Bridge Design Specifications (2017) and results from the literature on UHPC material property and structural behavior will be used as the basis for design guidance. A detailed literature review will be conducted on design of conventional concrete continuity joints and UHPC structural connections in other applications followed by survey of standard practice by state DOTs utilizing continuity connections. The collected information will be used to propose procedures similar to the AASHTO LRFD Bridge Design Specifications guidance for conventional concrete connections (2017).

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Literature Review

A comprehensive literature review including U.S. and international sources will be conducted to identify previous research on precast girders made continuous for live load, UHPC material properties relevant to continuity connection design, performance of different UHPC mixtures, and other types of UHPC connections. Specific attention will be paid to reinforcing bar/prestressing strand development within the joint, bond to conventional concrete, and tensile stress development within the continuity joint.

Previous research on continuity connections collected from the literature was examined including sources on design, testing, and construction practice from select states that have conducted similar studies. Of the many states investigated, Ohio, Pennsylvania, and New York provided some of the most promising literature. Selected studies include UHPC performance in several bridge applications across multiple states. Previous research collected on testing and modeling of conventional concrete continuity connections examined multiple configurations and presented mixed results on the effectiveness of these connections. Additionally, literature focused on UHPC characteristics relevant to design of live load continuity connections has been examined. This includes primarily tension and bond strengths of different UHPC materials and how those characteristics can be incorporated into an efficient connection detail and design procedures.

Task 2 – Examination of Current Design Practice

Current practice by U.S. state DOTs and in other countries relative to precast bridge girders made continuous for live load will be examined utilizing publicly available standard drawings and project information along with contacting representative state DOTs where this type of connection is used frequently. The project advisory panel will be consulted regarding DOT contacts for this task. These specific DOT personnel will be contacted for interviews rather than distributing a survey. Typical bridge configurations utilizing precast girders made continuous for live load, typical girder types made continuous for live load, prevalence of linkage blocks and continuity diaphragms, and typical details of these connections will all be examined. Any practices that have led to problems in the past will also be examined to identify how UHPC can best address these issues.

The student working on this project has extensively examined the existing AASHTO design provisions for conventional concrete connections of precast beams for live load continuity. The student continued examining additional code provisions on structural design with UHPC from both U.S. and international sources, specifically focused on modeling tension, compression, and bond behavior of UHPC to be used in the joint design process.

Standard drawings regarding continuity connections using conventional concrete from several state DOTs have been collected and examined. The student working on the project has compiled spreadsheets to document useful design parameters. These parameters include connection style, positive moment steel details, connection dimensions, and prestressing details. Sources were prioritized based on their relevance and breadth of technical detail. It was discovered during review of the standard drawings that many important design details are listed "as specified by the engineer". In order to collect data on these items, the student identified a series of existing bridges with continuity diaphragms cast using conventional concrete. The construction documents from these bridges were used to further understand the current practice of establishing live load continuity.

The examination of current design practice was also widened to include UHPC connections in general to identify typical details for reinforcing bar arrangements and joint widths. The primary applications of UHPC examined include transverse joints between precast deck panels, longitudinal closure joints, and link slabs.

Task 3 – Synthesis of Available Data and Current Design Practice for Design Guidance

Information identified in Tasks 1 and 2 will be used to reconcile differences between AASHTO LRFD design provisions for continuity joints, current construction practice, results from completed structural testing, and material behavior of UHPC. Care will be taken to complement and expand design guidance produced by current projects underway sponsored by NCHRP. Any gaps in knowledge will be identified for recommendation of additional work or limitations for the proposed Guide. Stress redistribution from the joint into the girders and required changes in design of the girders themselves will also be considered.

The primary goal of this project is to provide design guidance specific to UHPC. Therefore, current design documents including AASHTO LRFD Bridge Design Specifications, DOT specific design specifications, and technical papers on the characteristics of UHPC and conventional concrete were examined. The student used these documents to determine how the current design of conventional concrete diaphragms could be optimized by considering the superior material properties of UHPC. Standard drawings and those from completed bridges collected from state DOTs were examined to identify items for which additional design guidance is needed when UHPC is used instead of conventional concrete. Work continued on developing this design guidance based on the UHPC properties measured in previous research by the PIs and obtained in the literature by applying this information to a specific design example. Procedures developed relative to design of continuity connections using UHPC were also used to design laboratory-scale test specimens/connections that were constructed and tested as part of the graduate student's thesis research. These tests will be used to compare performance of designed connections to those made with UHPC, but designed with procedures intended for conventional concrete and tested as part of previous research (Casey 2019). Construction began on initial test specimens in May 2022 and continued throughout June, July, and August. All beams and most composite deck sections were cast by the end of August.

UHPC joints were cast between each set of two beam specimens to create six connection specimens. Each connection specimen consisted of two half-length beams with the joint in the middle that was tested on a simple span in either the upright orientation to create positive moment in the connection or upside down to induce negative moment in connection. Figure 1 shows beam specimens in each testing configuration. The connections utilized splice lengths for the negative moment region and strand embedments for restraint moments in the positive moment region based on results of previous research on UHPC. One connection was constructed with hooked strands having an embedment length determined by altering the design guidance provided in AASHTO LRFD based on Salmons and McCrate (1977) using results of previous testing of prestressing strand embedments in UHPC (Graybeal 2015). The other connection utilized straight strands extended into the joint. Both proprietary and non-proprietary UHPC were utilized for connections with hooked strands. One specimen from each pair was tested upright first to evaluate positive moment resistance and then tested to evaluated negative moment resistance. The other specimen was then tested for negative moment first followed by positive moment. This also allowed for examination of the effects of damage on structural performance. As of the end of November one specimen had been tested in both orientations with plans to test the remaining specimens in December and early January.

Figure 1. Continuity connection test (left) to induce positive moment in the connection and (right) to induce negative moment in the connection

Task 4 – Development of Design Examples and Training Materials

Two design examples will be prepared for two different bridge configurations that will discuss selection of the connection system used along with detailed design. Voice-over PowerPoint presentations will be created summarizing the proposed design guidance and the design examples.

Work continued on the two example problems based on in-service bridges. These examples extend the work done to design the laboratory scale specimens.

Task 5 – Reports and Guide for Design of UHPC Continuity Connections

Quarterly progress reports and a final report in Microsoft Word and ADA compliant Adobe Acrobat pdf will be provided at the end of the project year. The proposed guide will summarize design guidance synthesized as part of Task 3. This will include discussion of bridge types and configurations appropriate for UHPC continuity connections, selection of individual linkage blocks or full depth diaphragms, sizing of continuity joints, selection of reinforcement, and reinforcement detailing. Consideration of continuity connections as a potential retrofit connection will also be considered. Additional guidance will be provided for construction and quality control testing needed for UHPC continuity joints.

The current progress report is the seventh for the project and documents activities from September 1, 2022 to November 30, 2022.

5. Expected Results and Specific Deliverables

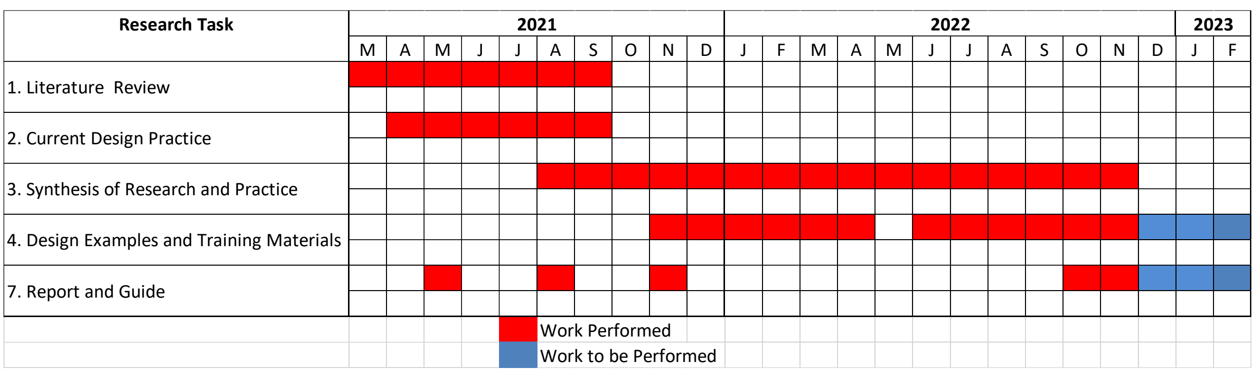
This project will develop design guidelines for UHPC connections of precast elements to make them continuous for live loads. This includes guidance for both new construction and retrofit to increase bridge capacity. Guidelines will be based on existing guidance for conventional concrete connections and completed research sponsored by the Oklahoma DOT and others.

As new construction methods are implemented and a greater emphasis is placed on extending life of existing bridges, continuity connections made with UHPC will become more important. A Guide for design of these elements will be needed by design engineers and readily available education materials will be necessary for the research results to make it into practice.

6. Schedule

Progress of tasks in this project is shown in the table below.

Item	% Completed
Percentage of Completion of this project to Date	90%



7. References

1- American Association of State Highway and Transportation Officials (AASHTO) (2017) AASHTO LRFD Bridge Design Specifications, (8th Edition), Washington, D.C.
2- Carbonell Munoz, M. A., Harris, D. K., Ahlborn, T. M., Froster, D. C. (2014) "Bond Performance between Ultrahigh-Performance Concrete and Normal-Strength Concrete," *ASCE Journal of Materials in Civil Engineering*, 26(8): 04014031.
3- Casey, C. (2019) "Ultra-High Performance Concrete for Connections of Precast, Prestressed Girders Made Continuous for Live Load," M.S. Thesis, the University of Oklahoma, Norman, OK.

4- Freyermuth, C. L. (1969) “Design of Continuous Highway Bridges with Precast, Prestressed Concrete Girders, *PCI Journal*, 14(2): 14-39.
5- Graybeal, B. (2006) Material Property Characterization of Ultra-High Performance Concrete, FHWA-HRT-06-103, Federal Highway Administration, McLean, VA.
6- Graybeal, B. (2010) “Behavior of Field-Cast Ultra-High Performance Concrete Bridge Deck Connections Under Cyclic and Static Structural Loading,” FHWA-HRT-11-023, Federal Highway Administration, McLean, VA.
7- Graybeal, B. (2011) “Ultra-High Performance Concrete,” FHWA-HRT-11-038, Federal Highway Administration, McLean, VA.
8- Graybeal, B. (2014) “Design and Construction of Field-Cast UHPC Connections,” FHWA-HRT-14-084, Federal Highway Administration, McLean, VA.
9- Graybeal, B. A. (2015) “Splice length of prestressing strands in field-cast UHPC connections,” *Materials and Structures*, 48(6): 1831-1839.
10- Hussein, H. H., Walsh, K. K., Sargand, S. M., and Steinberg, E. P. (2016) “Interfacial Properties of Ultrahigh-Performance Concrete and High-Strength Concrete Bridge Connections,” *ASCE Journal of Materials in Civil Engineering*, 28(5): 04015208.
11- John, E., Ruiz, E., Floyd, R., and Hale, W. (2011) “Transfer and Development Length and Prestress Losses in Ultra-High Performance Concrete,” *Transportation Research Record*, 2251:76-91.
12- Looney, T., Volz, J., and Floyd, R. (under review) “Behavior of a 3-Span Continuous Bridge Before and After Continuity Joint Replacement Using Ultra-High Performance Concrete,” *ASCE Journal of Performance of Constructed Facilities*.
13- Miller, R. (2004) “Connection of Simple-Span Precast Concrete Girders for Continuity,” NCHRP Report 519, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.
14- NCHRP 18-18 (2018) “Design and Construction of Deck Bulb Tee Girder Bridges with UHPC”, retrieved from: https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4204 on December 17, 2020.
15- Oesterle, R., Glikin, J. D., and Larson, S. C. (1989) “Design of Precast, Prestressed Bridge Girders Made Continuous,” NCHRP Report 322, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.
16- Rallabhandhi, S. (2016) “Evaluation of Ultra High Performance Concrete in Joints of Bridge Girders, M.S. Thesis, Missouri University of Science and Technology, Rolla, MO.
17- Russell, H. G. and Graybeal, B. A. (2013) “Ultra-High Performance Concrete: A State-of-the Art Report for the Bridge Community,” FHW-HRT-13-060, Federal Highway Administration, McLean, VA.
18- Saadeghvaziri, M., Spillers, W., and Yin, L. (2004). Improvement of Continuity Connection over Fixed Piers, FHWA-NJ-2004-017, Federal Highway Administration, Department of Transportation, Newark, NJ.
19- Swenty, M. and Graybeal, B. (2012) “Influence of Differential Deflection on Staged Construction Deck-Level Connections,’ FHWA-HRT-12-057, Federal Highway Administration, National Technical Information Service, Accession No. PB2012-111528.

20- Tayeh, B. A., Abu Bakar, B. H., Megat Johari, M. A., and Voo, Y. L. (2013) "Evaluation of bond strength between normal concrete substrate and ultra-high performance fiber concrete as a repair material," *Procedia Engineering*, 54: 554-563.