PRESTRESS LOSSES IN UHPC AND HYBRID PRECAST, PRESTRESSED BRIDGE GIRDERS

Quarterly Progress Report
For the period ending September, 2024

Submitted by:
PI – Royce Floyd, Ph.D., P.E., S.E.
Co-PI – Jeffery S. Volz, Ph.D. P.E., S.E.
Graduate Student- Omar Yadak

Affiliation: School of Civil Engineering and Environmental Science
University of Oklahoma
Norman, OK

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IBT/ABC-UTC
Florida International University
Miami, FL

1. Background and Introduction

Precast, prestressed concrete bridge girders are used extensively in conventional and accelerated bridge construction. As longer span girders are desired to reduce the number of supports and improve speed of construction the impacts of high prestressing force on the end regions of the beams become more significant. End region behavior of prestressed concrete girders has been a significant concern warranting numerous studies over the years focused on stress limits, prestress transfer length, cracking caused by the prestress, and shear capacity. Ultra-high performance concrete (UHPC) is a relatively recent advancement in cementitious composite materials with mechanical and durability properties far exceeding those of conventional concrete. These improved mechanical properties have the potential to mitigate the impacts of high stresses in prestressed girder end regions and to provide greater overall girder capacity. In addition, UHPC has the potential to increase the overall durability of these prestressed girders if used in areas of high exposure. However, little research has been conducted on the behavior of hybrid girders using UHPC in the end region or as a stay-in-place formwork shell. This project leverages results obtained through Oklahoma DOT support on long term behavior of full UHPC prestressed girders to design and evaluate time dependent behavior and strength of hybrid conventional self-consolidating concrete and UHPC girders. A total of 10 prestressed girders will be cast, instrumented, and tested and the results used to develop predictions for prestress loss behavior and recommendations for girder detailing

2. Problem Statement

Compared to conventional concrete, ultra-high performance concrete (UHPC) offers significantly improved mechanical and durability properties. However, these properties come at a noticeably higher cost. Cost-effective solutions employ UHPC strategically. One potential application of UHPC currently under consideration by FHWA and the Precast/Prestressed Concrete Institute (PCI) is UHPC precast, prestressed concrete bridge girders. The high compressive and tensile strength of UHPC combined with large diameter (0.7 in.) prestressing strands has the potential to create long-span and exceptionally durable girders. In addition, UHPC has the potential to reduce required shear reinforcement (Graybeal 2006, Lim and Hong 2016) and required supplemental reinforcement to control bursting and transfer stresses in the end regions caused by the large prestressing forces needed for long-span girders. While research has been conducted on some aspects of UHPC bridge girders dating back to the first decade of the 21st century, limited research has been conducted on the long-term behavior of these girders including prestress losses from creep and shrinkage. Additionally, the idea of a hybrid UHPC-conventional concrete prestressed girder has been explored and found to have potential for mitigating high stresses in the girder end regions (Torres et al. 2020), but little data on time-dependent behavior of these composite girders exist. The PIs were initially approached by the Assistant Bridge Engineer for maintenance from the Oklahoma Department of Transportation (ODOT) requesting the research team to consider the impact of UHPC on prestressed girder design in Oklahoma which became the basis of this proposal.

End region behavior of prestressed concrete girders has been a significant concern warranting numerous studies focused on stress limits, prestress transfer length, cracking caused by the prestress, and shear capacity. Long-span prestressed concrete girders require significant prestressing forces that result in high stresses in the beam end regions that can lead to cracking for certain geometries. Cracking can be mitigated by specific detailing to adjust the stresses generated from the prestress or to reinforce against cracking (Ronanki et al. 2017, Ross et al. 2013, Tadros et al. 2010). End region reinforcement and detailing can also have a significant impact on girder capacity (Ross et al. 2013). Prestress transfer and development length can have a significant impact on the behavior of prestressed concrete girder end regions as they control how quickly stresses resulting from the prestress develop along the length of the beam and how ultimate capacity of the end region develops. UHPC has been shown to result in significantly shorter transfer and development lengths than for conventional concrete (Graybeal 2006, John et al. 2011), which can lead to higher tension and compression stresses in the girder end region.

Prestressed concrete girders using UHPC for the entire girder have been examined by several previous research projects including implementation in actual bridges in the state of Iowa and in countries outside of the United States (FHWA 2022). The Precast/Prestressed Concrete Institute has funded research focused on UHPC for precast and prestressed concrete elements (PCI 2022). FHWA has conducted full-scale girder testing to evaluate flexural, shear, bond, (Graybeal 2006) and long-term (Mohebbi and Graybeal 2022) behavior of UHPC girders and have developed effective methods for finite element modeling of UHPC girders that match well with experimental data (Chen and Graybeal 2010). Hybrid UHPC-SCC bridge girders have been investigated by researchers at the University of Florida to evaluate performance of UHPC end regions. These researchers indicated that use of UHPC in the end regions results in less cracking from the applied prestress, even with reduced reinforcement, and increased shear capacity (Torres et al. 2020). They also developed methods for creating an effective UHPC to SCC interface (Voss et al. 2019) and methods for finite element modeling of UHPC end regions (Torres et al. 2020).

These previous studies generally focused on structural behavior at failure, stress levels in the end regions, and design guidelines. Research by FHWA included detailed measurement and prediction of prestress losses for full UHPC girders (Mohebbi and Graybeal 2022), and others have reported lower overall prestress losses for UHPC prestress beams (John et al. 2011), but little information was found for composite UHPC-conventional concrete girders. In addition, precast UHPC shells have been shown to be effect for use as stay-in-place formwork for bridge columns (Caluk et al. 2019) and other ABC elements (Azizinamini and Khodayari 2023), but no data was found on using this type of stay-in-place formwork for prestressed concrete elements. Precast, prestressed bridge girders are a key component of many bridge systems and ABC methods. Increased span lengths associated with UHPC girders and improved performance from hybrid UHPC-conventional SCC girders have the potential to reduce the required number of spans on a given bridge, thereby shortening the required construction time and improving the overall durability of the bridge system.

3. Objectives and Research Approach

There are three objectives of the proposed research. The first objective is to measure prestress losses for full UHPC prestressed bridge girders. The second objective is to evaluate the effect of a hybrid UHPC-conventional concrete girder design on prestress loss behavior. The third objective is to evaluate the effectiveness of different design details for mitigating stresses in the girder end region and their effect on hybrid girder capacity.

This project utilizes results of research conducted at OU to evaluate long-term performance of precast/prestressed UHPC and hybrid UHPC-conventional self-consolidating concrete (SCC) bridge girders. UHPC mix designs developed at OU through funding by ODOT and ABC-UTC will be utilized in this study. In Task 1, laboratory-scale prestressed beams designed to have a service stress state similar to UHPC girders tested in previous research by FHWA and others are cast at OU and instrumented for measurement of end region and mid-span strain. These UHPC girders will have variations in applied stress and end region detailing to evaluate time-dependent impacts of applied stress and detailing on time-dependent behavior. Hybrid conventional SCC and UHPC girders based on designs developed by the co-PI and a girder using a UHPC shell as stay-in-place formwork are cast and tested for comparison. These girders utilize UHPC only in the regions of high stress indicated by the results of Task 1. All Girders will be monitored over time to measure losses due to elastic shortening, creep, and shrinkage. Different design details proposed for reducing stresses in the end region of prestressed girders will also be evaluated in the hybrid girders to determine the effects on strains developed in the girder. Finally, UHPC material property measurements (modulus of elasticity, creep, and shrinkage) from previous research at OU and in the literature are used to develop prediction models for comparison with the measured losses over time.

4. Description of Research Project Tasks

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

Task 1 – Design, Construct, and Monitor Full UHPC Girder Specimens.

A literature review will be conducted to identify previous research on UHPC prestressed concrete girders to determine the maximum stresses applied in both tension and compression. Information identified from this review will also be used to identify required reinforcing details to reduce potential for end region cracking, camber, and prestress losses. Girder specimens will be designed as approximately half-scale elements to utilize existing formwork, stay within the constraints of the OU prestressing bed, and to obtain the required stress states. Four girder designs will be developed to vary end region stress in tension and compression and to vary end region reinforcement detailing. Girders will be cast at the OU Fears Structural Engineering Laboratory using the OU-developed J3 UHPC mix design and will be instrumented with vibrating wire strain gages at mid-span to monitor prestress losses and in the end regions to evaluate stresses resulting from the prestress force. Specimens will be evaluated for cracking at the point of prestress release and over time and will be monitored to evaluate prestress losses over time. The girders will be monitored over time with readings taken continually using a dedicated datalogger.

Girder specimens were designed to utilize existing formwork, stay within the constraints of the OU prestressing bed, and to match service level stress states identified in the literature review. The selected cross-section is shown in Figure 1 and is based on an approximately ½ scale AASHTO Type II girder. The length of the girder was selected as 14 ft to limit the required amount of material even though the existing formwork was 18 ft. Prestressing reinforcement consisted of six 0.5 in. special prestressing strands arranged in one row of four and one row of two. A reduced web thickness was used at the end of the specimens to facilitate shear failure during planned shear testing. No mild steel was included in the UHPC girder design except for two double No. 3 stirrups at the end region (Figure 2) even though the applied tension stress at prestress release was determined to be high.

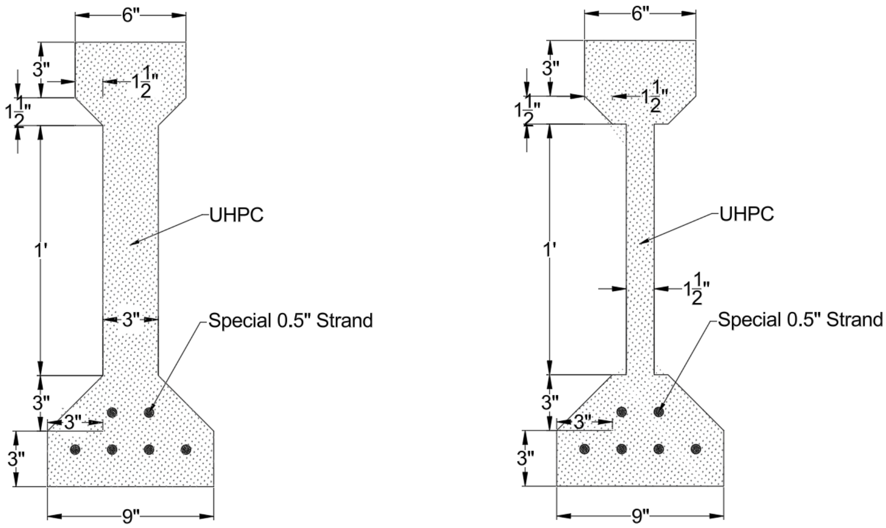


Figure 1. Cross section view of UHPC half-scale AASHTO Type II girder at (left) mid-span and (right) end region

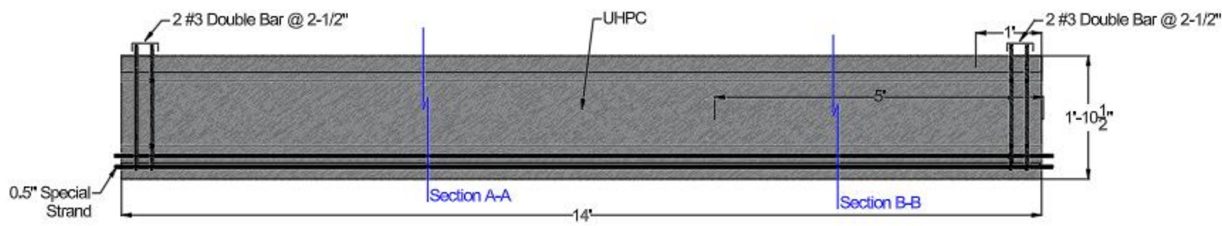


Figure 2. Elevation view of full UHPC prestressed girder specimen

Task 2 – Design, Construct, and Monitor Hybrid Girder Specimens.

Six hybrid UHPC-SCC precast, prestressed concrete beams will be cast at Fears Lab on the OU campus using designs developed based on the results of Task 1. The different designs will be based on the maximum stresses measured in the full UHPC beams tested in Task 1 and will result in variations in reinforcing details and combination of SCC and UHPC. At least one specimen will consist of a UHPC stay-in-place formwork shell that will be filled with SCC and left in place to provide protection of the conventional concrete against corrosion. Interfaces between the UHPC and SCC will be based on results of research completed by the co-PI. All specimens will be instrumented with strain gages placed at midspan and within the UHPC portion to evaluate strain development along the length of the girder and prestress losses over time. The girders will be monitored over time with readings taken continually with a dedicated data logger

The design of Hybrid girders was finalized in terms of the interface texture between the two materials, and cross-section of the girders. Girder specimens were designed to have the same cross-section, prestressing, and stress states as the full UHPC girders including a reduced web thickness within the UHPC end region (Figure 1). Calculations of allowable stresses, flexural capacity, shear capacity and prestress losses were done using the AASHTO LRFD Bridge Design Specifications (2017) to help identify the reinforcement needed for the SCC portion of the girders, specifically relative to shear and to resist tensile stresses at prestress release. Those calculations were also taken as a reference for evaluating the girders' behavior during testing. All shear reinforcement was continued past the top of the girders to be used for connecting the deck sections to be added before shear testing. Since no shear steel was included in the UHPC portion, double No. 4 bars were included just at the intended deck interface similar to those used by Choate (2023). The final design for a hybrid girder with a 6 ft UHPC end region is shown in Figure 3.

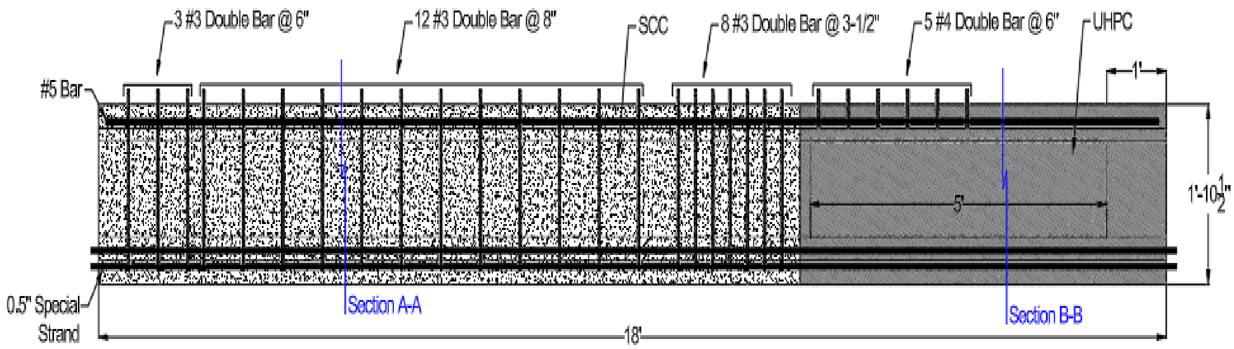


Figure 3. Elevation view of hybrid prestressed concrete girder specimen

Originally it was planned that the stay-in-place formwork prestressed girders would use the same cross-section as the other hybrid girders, but the cross section was changed to be a 9 in. by 16 in. rectangular cross-section (Figure 4) to simplify formwork construction for this proof of concept. The dimensions were selected to match the applied stresses of the other beam specimens with the same number of strands and locations. The length of this type of girder is 14 ft not 18 ft, similar to the UHPC girders.

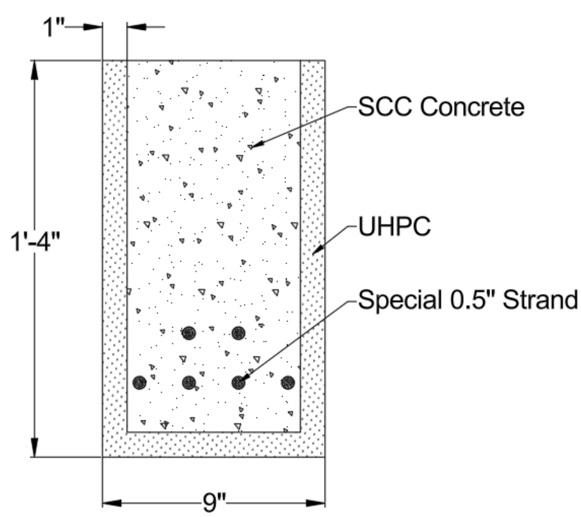


Figure 4. UHPC stay-in-place formwork specimen cross-section design

The large structural testing project that occupied the Fears Lab strong floor through April, May, June, and July and preventing construction of prestressed girders was completed and the first set of Hybrid girders was cast. All girders were instrumented with vibrating wire strain gages placed at mid-span and each end region to measure deformation and prestress losses over time. Hybrid girders were cast first to have as much time as possible for prestress loss measurement. A picture of completed hybrid specimens is shown in Figure 5.

Figure 5. Completed hybrid girder specimens

Task 3- Prediction of Time-Dependent Behavior.

A prestress loss prediction model using existing model structures for creep and shrinkage will be developed utilizing data from material property testing at OU and in the literature and will be compared to experimentally measured prestress losses for both the full UHPC and hybrid girder specimens.

This task is planned to commence in Quarter 4 of 2024.

Task 4- Shear Testing.

All girder specimens will tested in shear to evaluate strength of the girder end regions and to evaluate effectiveness of the composite behavior of the UHPC-SCC hybrid sections. These tests will be conducted near the end of the project, after the prestress losses have stopped changing significantly.

This task is planned to commence in Quarter 4 of 2024.

Task 4- Final Report and Training Materials.

A final report will be prepared compiling the results of all work in the project and a one hour pre-recorded training module will be developed to disseminate the results of this research.

This task is planned to commence in Quarter 4 of 2024.

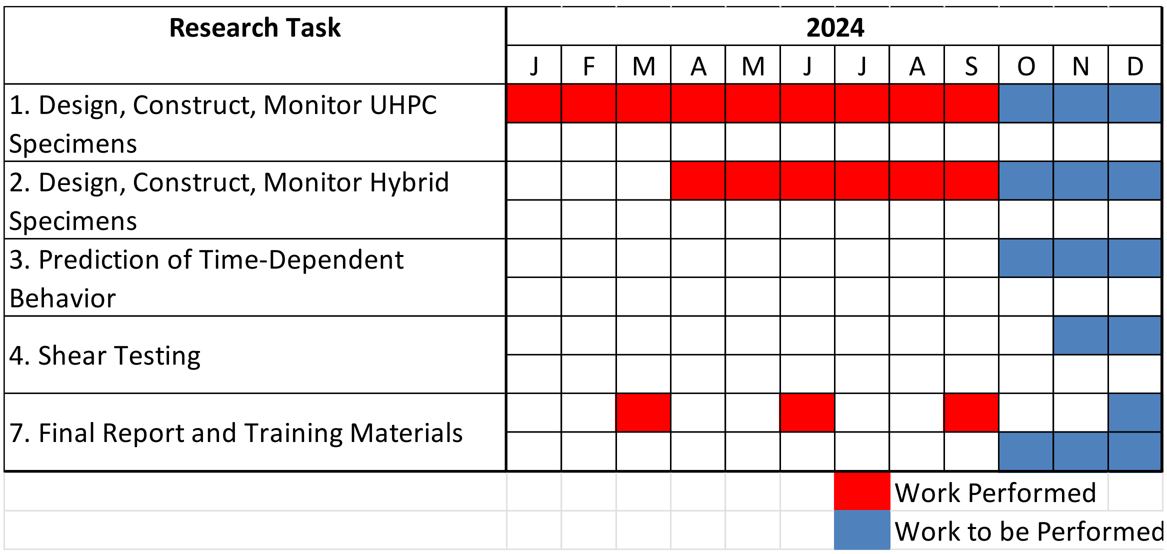
5. Expected Results and Specific Deliverables

It is anticipated that the project will produce new data and draft prediction models for time dependent behavior of ultra-high performance concrete (UHPC) bridge girders. A final report documenting findings of the experimental testing and draft prediction models for creep and shrinkage losses in prestressed bridge girders constructed with UHPC will be produced. One journal paper is anticipated to be submitted based on this project, at least one presentation will be made to ODOT officials and a one hour pre-recorded training module will be developed. Potential outcomes include an implementation project and/or follow on study sponsored by ODOT. Potential impact includes incorporation of results in design standards for UHPC prestressed girders.

6. Schedule

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

Item	% Completed
Percentage of Completion of this project to Date	35%



7. References

1- Azizinamini, A. and Khodayari (2023) "UHPC Based Solutions for Accelerated Bridge Construction," *Third International Interactive Symposium on Ultra-High Performance Concrete 2023*, Wilmington, DE, June 4-7, 2023, Paper No. 137.

2- Caluk, N., Mantawy, I., and Azizinamini, A. (2019) "Durable Bridge Columns using Stay-In-Place UHPC Shells for Accelerated Bridge Construction," *Infrastructures*, 4(2), 25; https://doi.org/10.3390/infrastructures4020025

3- Chen, L. and Graybeal, B. A. (2010) "Finite Element Analysis of Ultra-High Performance Concrete: Modeling Structural Performance of an AASHTO Type II Girder and a 2nd Generation Pi-Girder," *Report No. FHWA-HRT-11-020*, Federal Highway Administration, McLean, VA.

4- Choate, J. (2023) "End-Region Evaluation of Hybrid Ultra-High-Performance Concrete/Conventional Concrete Prestressed Girders," Ph.D. Dissertation, The University of Oklahoma, Norman, OK.

5- Federal Highway Administration (2022) "Ultra-High Performance Concrete", U.S. Department of Transportation Federal Highway Administration, retrieved from https://highways.dot.gov/research/structures/ultra-high-performance-concrete/ultra-high-performance-concrete, November 16, 2023.

6- Graybeal, B. A. (2006) "Structural Behavior of Ultra-High Performance Concrete Prestressed I-Girders," *Report No. FHWA-HRT-06-115*, Federal Highway Administration, McLean, VA.

7- John, E. E., Ruiz, E. D., Floyd, R. W., and Hale, W. M. (2011) “Transfer and Development Lengths and Prestress Losses in Ultra-High Performance Concrete Beams,” *Transportation Research Record: Journal of the Transportation Research Board*, No. 2251: 76-81, doi: 10.3141/2251-08.
8- Lim, W. Y. and Hong, S. G. (2016) “Shear Tests for Ultra-High Performance Fiber Reinforced Cocnrete (UHPFRC) Beams with Shear Reinforcement,” *International Journal of Concrete Structures and Materials*, 10(2): 177-188.
9- Mohebbi, A. and Graybeal, B. (2022) “Prestress loss model for ultra-high performance concrete,” *Engineering Structures*, 252: 113645, https://doi.org/10.1016/j.engstruct.2021.113645
10- PCI Concrete Materials Technology Committee (2022) *Guidelines for the Use of Ultra-High Performance Concrete (UHPC) in Precast and Prestressed Concrete*, Precast/Prestressed Concrete Institute, Chicago, IL.
11- Ronanki, V. S., Burkhalter, D. I., Aaleti, S., Song, W., and Richardson, J.A. (2017) “Experimental and analytical investigation of end zone cracking in BT-78 girders,” *Engineering Structures*, 151: 503-517.
12- Ross, B. E., Consolazio, G. R., and Hamilton, H. R. (2013) “End Region Detailing of Pretensioned Concrete Bridge Girders,” Final Report BDK75 977-05, Florida Department of Transportation, Tallahassee, FL, 581 pp.
13- Tadros, M. K., Badie, S. S., Tuan, C. Y. (2010) “Evaluation and Repair Procedures for Precast/Prestressed Concrete Girders with Longitudinal Cracking in the Web,” *NCHRP Report 654*, Transportation Research Board, Washington, D.C.
14- Torres, E., Hamilton, H. R., and Consolazio, G. R. (2020) “Hybrid Prestressed Concrete Bridge Girders Using Ultra-High Performance Concrete,” Final Report BDV31-977-101, Florida Department of Transportation, Tallahassee, FL.
15- Voss, M., Torres, E., Alrashidi, R. S., Riding, K. and Hamilton, T. (2019) “Evaluation of Bond Strength of Joints in Hybrid UHPC and SCC Members”, *International Interactive Symposium on Ultra-High Performance Concrete* 2(1). doi: https://doi.org/10.21838/uhpc.9659)