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16. Abstract This project evaluated long-term performance of precast/prestressed ultra-high performance concrete (UHPC) and hybrid UHPC-conventional self-consolidating concrete (SCC) bridge girders. The objectives of the research were to measure prestress losses and evaluate the effectiveness of different design details for mitigating stresses in the girder end region including their effect on hybrid girder capacity. Ten approximately half-scale AASHTO Type-II prestressed concrete girder specimens were cast, instrumented, and monitored over time to measure immediate and time-dependent prestress losses. These included one SCC specimen, three full UHPC specimens, five hybrid specimens consisting of SCC with UHPC in one end region, and one specimen consisting of a stay-in-place UHPC formwork shell and conventional concrete infill. UHPC mix designs developed at OU through funding by ODOT and ABC-UTC were utilized in this study. Different design details developed for reducing stresses and mitigating cracking in the end region of prestressed girders were also evaluated in the hybrid girders to determine the effects on girder performance. Five hybrid prestressed girders were successfully cast with a bi-fluid interface. The use of a wooden divider at the interface between UHPC and SCC helped to control the flow rate of the UHPC and SCC and maintain the two materials separated until the casting process was done. The UHPC end regions for all the hybrid prestressed girders had higher compressive stress compared to the SCC end regions, no cracks were observed in those end region after 150 days. However, some cracks were observed at the SCC end regions for some of the hybrid prestressed girders and the SCC girder. The time-dependent (creep and shrinkage) prestress losses behavior of the hybrid prestressed girders was similar to that of the SCC prestressed girder and full UHPC prestressed girders, indicating that the hybrid design did not appear to have an impact on the prestress losses at midspan. The length of the overall UHPC section in the hybrid prestressed girder did not have an effect on prestress loss behavior at midspan and the UHPC durability to withstand high compressive stresses at the end region.					
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Prestress Losses in UHPC and Hybrid Precast, Prestressed Bridge Girders

Final Report

October 2025

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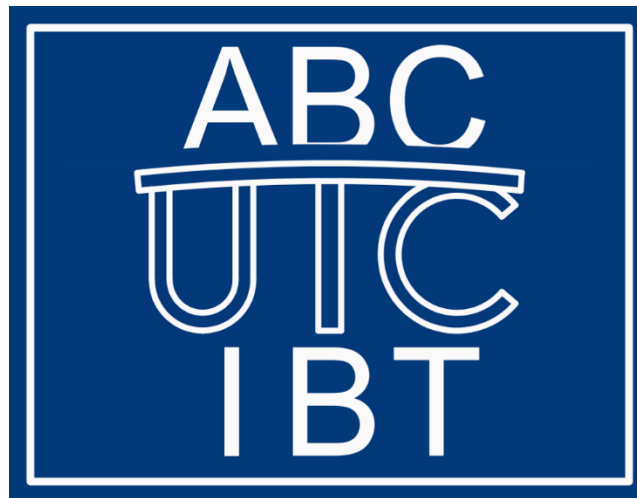
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Chapter 1. Introduction

1.1. Background

1.1.1. *Overview*

The Federal Highway Administration (FHWA) and state Departments of Transportation (DOTs) have and are currently sponsoring research studies for new techniques and designs related to Accelerated Bridge Construction (ABC). ABC has several advantages over traditional construction as it reduces the delivery time of a project, provides a safer work zone, and reduces interruption of traffic flow (Culmo 2011). Precast, prestressed concrete bridge girders are used extensively in conventional and accelerated bridge construction. The design of prestressed girders aligns well with the principles of ABC for faster construction, more sustainable service life, and longer span length. As longer-span girders are desired to reduce the number of supports and improve the 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.

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.

Prestressing forces are expected to reduce over the service life of the structure due to a variety of factors. Immediate prestress losses include elastic shortening, anchorage slippage, and friction, and time-dependent prestress losses include effects of creep, shrinkage, and strand relaxation. The reduction in prestress can significantly affect the performance of a prestressed concrete structure, so prestress losses are considered when designing a prestressed concrete structural element. Time-dependent prestress losses have received more attention in research than immediate losses due to their long-term effect on the effective prestressing forces (Abdel-Jaber et al. 2018) and difficulty of prediction. There have been numerous research studies on prestress losses in conventional prestressed concrete and current design codes include prediction methods. However, limited research has been conducted on the long-term behavior of ultra-high performance concrete (UHPC) and hybrid UHPC-conventional concrete prestressed girders, specifically prestress losses from creep and shrinkage.

1.1.2. *UHPC Prestressed Girders*

Ultra-high performance concrete (UHPC) offers significantly improved mechanical and durability properties compared to conventional concrete. However, these properties come at a noticeably higher cost. Cost-effective solutions employ UHPC strategically. One potential application of UHPC examined 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 have the potential to create long-span and exceptionally durable girders (PCI 2022, FHWA 2022). 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 due to the presence of a high percentage of steel fibers.

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; Taylor et al. 2013). The Precast/Prestressed Concrete Institute has funded research focused on UHPC for precast and prestressed concrete elements as well (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).

Steinberg (2009) focused on evaluating the flexural capacity of UHPC prestressed bridge girders based on three analytical methods. They also performed Monte Carlo simulations to examine the effect of changing given parameters on the flexural strength of the girder (Steinberg 2022). Additionally, Li et al. (2022) evaluated the flexural cracking behavior and flexural capacity of long-prestressed UHPC T-shaped girders and developed a non-linear analysis model to assess the non-linear flexural behavior based on the experimental data (Li et al. 2022).

In terms of shear design for UHPC prestressed girders, El-Helou and Graybeal (2022) evaluated shear behavior of six pretensioned UHPC bulb-tee girders. They studied the impact of several parameters, including UHPC product, the height of the beam and thickness of the web, the number of prestressing strands, and the presence of shear reinforcement in the beams on shear behavior. Shear capacity was heavily dependent on the tensile characteristics of the UHPC (El-Helou and Graybeal 2022). Feng et al. (2023) investigated the shear behavior of UHPC prestressed girders without any shear reinforcement. Fiber percentage by volume was a critical parameter in increasing post-cracking shear resistance and toughness. Increasing the fiber percentage in the UHPC matrix from 1.0% to 1.5 % and 2.0 % increased the toughness by 9.5% and 46.1%, respectively (Feng et al. 2023). Other research studies also investigated the shear performance of UHPC prestressed beams with and without conventional shear reinforcement (Voo et al. 2006, Baby et al. 2013, Pourbaba et al. 2018, Foster and Bentz 2024).

1.1.3. Hybrid UHPC-Conventional Concrete Prestressed Girders

The concept of a hybrid UHPC-conventional concrete prestressed girder has been explored and found to have the potential for mitigating high stresses in the girder end regions (Torres et al. 2020), but little data on the time-dependent behavior of these composite girders exists. Hybrid UHPC-SCC bridge girders have been investigated by researchers at the University of Florida to evaluate the 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 have generally focused on structural behavior at failure, stress levels in the end regions, and design guidelines.

Li et al. (2020) examined the flexural properties of composite prestressed UHPC-Normal concrete (NC) T-girders. They tested 10 large-scale composite prestressed girders and 1 NC prestressed girder along with an analytical model to simulate the flexural properties of composite girders (Li et al. 2020). Katlav and Ergen (2024) presented data-driven machine learning (ML) models to understand the flexural behavior of UHPC-NC hybrid beams and evaluate the feasibility of the models for predicting the flexural capacity of the composite design (Katlav and Ergen 2024). A research study conducted at the University of Oklahoma (OU) by Choate (2023) explored the concept of hybrid UHPC-conventional concrete girders and evaluated the shear behavior of the end regions and continuity across the interface. With proper interface methods and textures, the performance of the large-scale hybrid girders matched the monolithic members with added advantages resulting from the presence of UHPC in the end regions (Choate 2024). Another research study by Vidya et al. (2019) evaluated the performance of a long-span hybrid girder including UHPC in critical regions of normal weight concrete girders (Vidya et al. 2019). Experimental work and finite element model were conducted to investigate the performance of the hybrid girder and to study the interface between the concretes. The failure load and slip values prediction by the model were within 95% of the experimental measured values, indicating good bonding between the materials (Vidya et al. 2019).

In addition, precast UHPC shells have been shown to be effective 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.

1.1.4. Prestress Losses of Full UHPC and Hybrid UHPC-Conventional Concrete Prestressed 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 (Liu et al. 2024). The design of prestressed girders requires a proper understanding of prestress losses to avoid service load-cracking and durability concerns (Garber et al. 2016). 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 prestressed beams (John et al. 2011). Another research study by Ammari and Ahlborn (2023) showed that thermal treatment of UHPC led to improve the properties of UHPC, including time-dependent behavior, and potentially reduced prestress losses (Ammari and Ahlborn 2023). Little information was found on prestress losses of composite UHPC-conventional concrete girders.

1.2. Problem Statement

This project evaluated 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 were utilized in this study. All girders were monitored over time to measure prestress losses due to elastic shortening, creep, and shrinkage. Different design details developed for reducing stresses and mitigating cracking in the end region

of prestressed girders were also evaluated in the hybrid girders to determine the effects on girder performance.

1.3. Research Scope, Objectives and Tasks

1.3.1. Research Scope and Objectives

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

1.3.2. Research Tasks

Four tasks were set to accomplish the objectives mentioned in this research study. This report discusses tasks 1-3, and task 4 will be completed in the future once the prestress losses measurements are completed.

- 1) Design, construct, and monitor hybrid prestressed girder specimens.
- 2) Design, construct, and monitor full UHPC prestressed girder specimens.
- 3) Prediction of time-dependent behavior.
- 4) Shear testing of UHPC and hybrid prestressed girders.

Chapter 2. Prestressed Girders Design

Nine approximately half-scale AASHTO Type II girders and one UHPC stay-in-place formwork shell girder were designed and constructed at Fears Structural Engineering Laboratory at the University of Oklahoma (OU). Girder specimens were designed to utilize existing formwork, stay within the constraints of the OU prestressing bed, and obtain the required stress states. *Figure 1* presents the dimensions of the approximately half-scale AASHTO Type II girder.

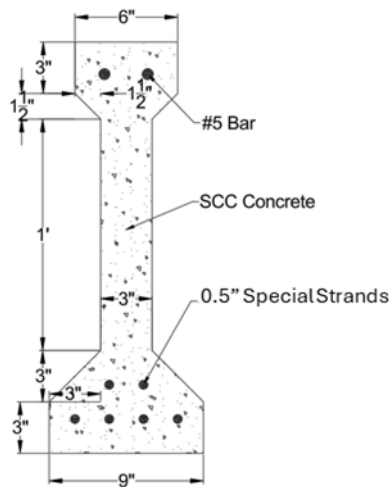


Figure 1. Dimensions of a half-scale AASHTO Type II girder

The AASHTO LRFD Bridge Design Specifications (2017) were used to evaluate the maximum stresses applied to the girders from the prestress in tension and compression and the allowable stresses at the end regions and midspan. Table 1 presents the calculated and allowable stresses at prestress release for a 180 ksi prestressing stress and a concrete compressive strength of 7,400 psi. The concrete compressive strength was chosen based on the mix design to be used for self-consolidating concrete (SCC) beam construction.

Table 2 shows the calculated and allowable stresses at prestress release for 202.5 ksi prestressing stress and a concrete compressive strength of 7,400 psi.

Table 1. Calculated and allowable stresses of an SCC girder for 180 ksi prestressing stress

Location	Stresses	Calculated (psi)	Allowable (psi)
End	f_{tension}	1,022	650
End	$f_{\text{compression}}$	3,618	4,440
Midspan	f_{tension}	931	650
Midspan	$f_{\text{compression}}$	3,546	4,440

Table 2. Calculated and allowable stresses of an SCC girder for 202.5 ksi prestressing stress

Location	Stresses	Calculated (psi)	Allowable (psi)
End	f_{tension}	1,225	650
End	$f_{\text{compression}}$	4,337	4,440
Midspan	f_{tension}	1,134	650
Midspan	$f_{\text{compression}}$	4,265	4,440

The J3 UHPC mix design developed at OU through funding by ODOT and ABC-UTC was utilized in this study (Looney et al. 2019). The concrete properties and characteristics are outlined in Looney et al. (2019). The composition of the J3 UHPC mix with a 2% steel fiber content by volume is shown in Table 3. The mixing procedure used followed that of Looney et al. (2019), and the flow of J3 UHPC was measured using ASTM C1856 (2017).

Table 3. Weight ratios of J3 UHPC Composition

Constituent	Mix Proportion
Type I Cement	0.6
Silica Fume	0.1
Slag Cement	0.3
Masonry Sand (1:1 agg/cm)	1.0
w/cm	0.2
Steel Fibers	2% by volume
High Ranger Water Reducer Admixture	18-24 oz/cwt

Table 4 presents the mix design used for casting the SCC portion of the girder specimens. A high-range water reducing (HRWR) admixture was added to achieve the targeted slump flow of 25 to 27 in. for the SCC mix.

Table 4. Self-Consolidating Concrete mix design (quantities based on SSD)

Material	Quantity
Sand (lb/yd ³)	1476
5/8 in. Coarse Aggregate (lb/yd ³)	1445
Cement (lb/yd ³)	825
Water (lb/yd ³)	289
Adva Cast 575 HRWR Admixture (fl oz/cwt)	7-10

2.1. Parameter Matrix

Five hybrid UHPC-self-consolidating concrete (SCC) prestressed girders, three full UHPC prestressed girders, one SCC prestressed girder (control specimen), and one UHPC stay-in-place formwork prestressed girder were designed in order to evaluate the end region stresses and prestress losses. Shear testing will be conducted on those girders after collecting the necessary data for the time-dependent prestress losses. The hybrid prestressed girders and the control specimen were 18 ft long, whereas the UHPC and concrete shell specimens were 14 ft long to accommodate the availability of UHPC material.

Table 5 presents the parameter matrix for all the prestressed girders tested in this research. In

Table 5 and throughout the report, UHPC-CS and H-UHPC-SCC are used for “UHPC concrete shell” and “hybrid UHPC-self-consolidating concrete”, respectively.

Table 5. Parameter matrix for the prestressed girder specimens

Specimen	Prestressing Stress (ksi)	Overall UHPC Length (ft)	Steel Fiber % by Volume	End Region Reinforcement	Top Flexural Reinforcement
SCC	180	N/A	N/A	N/A	Yes
H-UHPC-SCC 1	180	5	2	N/A	Yes
H-UHPC-SCC 2	180	5	2	N/A	Yes
H-UHPC-SCC 3	202.5	5	2	N/A	Yes
H-UHPC-SCC 4	202.5	3	2	N/A	Yes

Specimen	Prestressing Stress (ksi)	Overall UHPC Length (ft)	Steel Fiber % by Volume	End Region Reinforcement	Top Flexural Reinforcement
H-UHPC-SCC 5	180	3	2	N/A	Yes
UHPC 1	180	5	2	Yes	No
UHPC 2	180	5	1	Yes	No
UHPC 3	202.5	5	2	Yes	Yes
UHPC-CS 1	202.5	N/A	2	Yes	Yes

2.2. Hybrid UHPC Prestressed Girders (H-UHPC-SCC)

The design of the hybrid girder specimens was based on previous research by Choate (2023). One end of the hybrid UHPC prestressed girders was designed with UHPC, and the rest was designed with SCC. The length of the girders was chosen to be 18 ft to match existing formwork and previous girders constructed at OU. As continuity in composite members is important, the BiFluid interface between the UHPC and SCC described by Choate (2023) was chosen due to its excellent results in continuity and simple construction (Choate 2023). The BiFluid interface means that both the UHPC and SCC were cast simultaneously with the rates monitored to maintain the same height of both materials throughout casting.

All the girders were designed to fail in shear for a load placed near the end region to evaluate strength of the girder end regions and to investigate the effectiveness of the UHPC-SCC hybrid prestressed girders composite behavior. These tests will be conducted after the completion of prestress losses measurements. Substantial flexural reinforcement, including a deck section above the girder, will be added to ensure shear failure while remaining within the acceptable flexural capacity limits. Shear capacity was calculated from design equations collected from Graybeal (2023), the Japanese Society of Civil Engineers (JSCE) provided in Hamilton et al. (2020), and the French Standard Institute (2016). The UHPC shear strength was used as the baseline for minimum design capacity. The SCC portion was designed following the ACI Detailed Method to ensure that the shear capacity near the interface was equivalent to the capacity of the UHPC. The minimum flexural capacity of the girder was then determined based on the load required to cause shear failure in the UHPC and ensure a shear failure prior to a flexural failure (Choate 2023). Since the shear resistance of UHPC was high due to incorporating 2% steel fiber, the UHPC web section within the overall UHPC section was reduced to half the width of the web. Reduced web section lengths of 4 ft and 2 ft were chosen for the 5 ft and 3 ft overall UHPC sections, respectively. Figure 2 provides a cross-section view of the UHPC end in the reduced web portion.

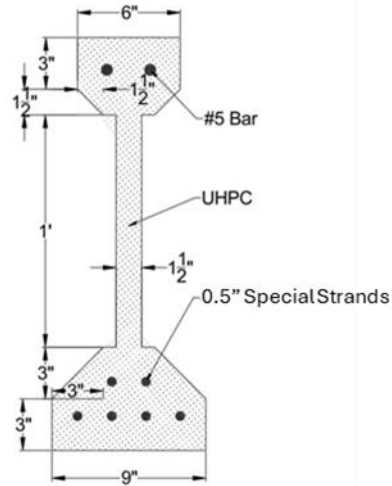


Figure 2. Girder cross section view of the UHPC end

Allowable and concrete stresses at end regions and midspan were calculated following AASHTO LRFD Bridge Design Specifications (2020) for both prestressing stress of 180 ksi and 202.5 ksi. The tensile, compressive and allowable stresses of the prestressed girders at end regions are presented in Figure 3-a and Figure 3-b, respectively. The stresses were calculated using the SCC compressive strength of 7,400 psi at release. In both prestressing stress cases, the compressive stress did not exceed the allowable, however, the tensile stress exceeded the allowable stress. Top steel reinforcement was added to accommodate that high tensile stress in the hybrid and conventional concrete beams.

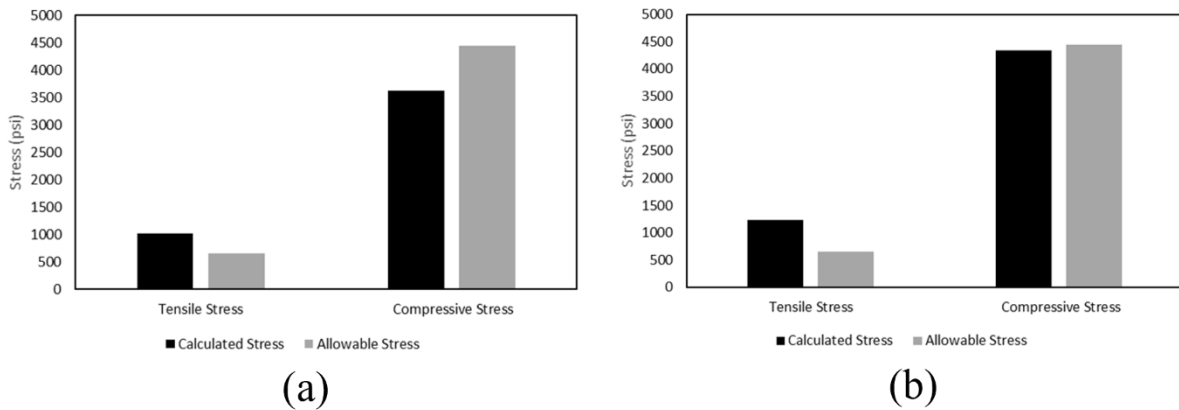


Figure 3. Tensile, compressive and allowable stresses for (a) 180 ksi and (b) 202.5 ksi prestressing stress

The SCC portion of the girder near the interface with the UHPC section was designed to have equal shear strength to the UHPC portion near the interface using the ACI Detailed Method. The same methodology was applied to design the vertical reinforcement for the remaining SCC section, including the end opposite to the interface. The shear design included 8 double No. 3 bars placed at 3.5 in. on center near the interface and 12 double No. 3 bars placed at 8 in. on center for the remaining SCC section of the girder. These stirrups extended from the top of the beam and will connect to the deck section that will be cast in the future to resist horizontal shear between the

deck and the girder. Horizontal shear between the deck and the UHPC will be resisted by 5 double No. 4 bars spaced at 6 in. and extending from the top of the beam into the deck. The overall flexure and shear reinforcement for a 5 ft reduced web section is shown in Figure 4.

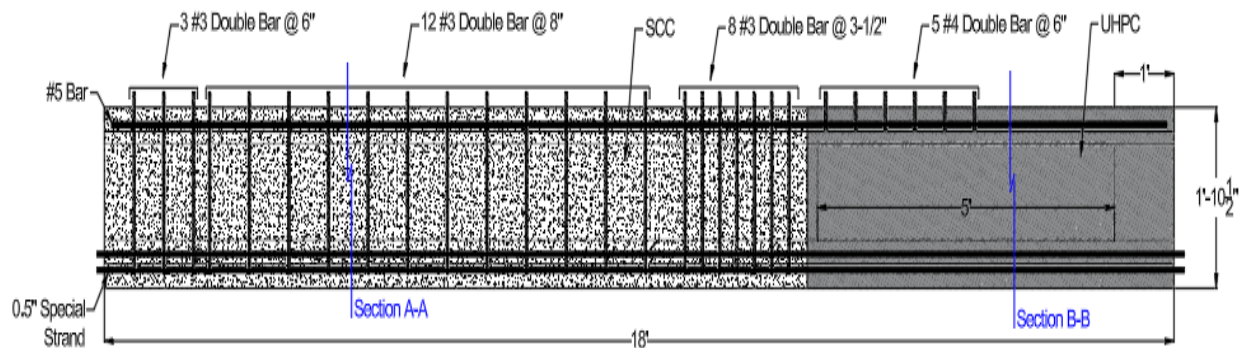


Figure 4. Flexure and shear reinforcement of a hybrid girder with a 5 ft reduced web section

2.3. Full UHPC Prestressed Girders

All the UHPC prestressed girders were the same approximately half-scale AASHTO Type II girder section used for the hybrid girders. They were 14 ft long instead of 18 ft to minimize the amount of material required and since UHPC has shorter prestress transfer and development lengths based on previous studies. The design did not contain shear reinforcement and did not include top steel to offset the high tensile stresses from the prestressing. Only bursting reinforcement was added at both ends of the UHPC prestressed girders in accordance with AASHTO section 5.9.4.4 (AASHTO 2020) as shown in Figure 5.

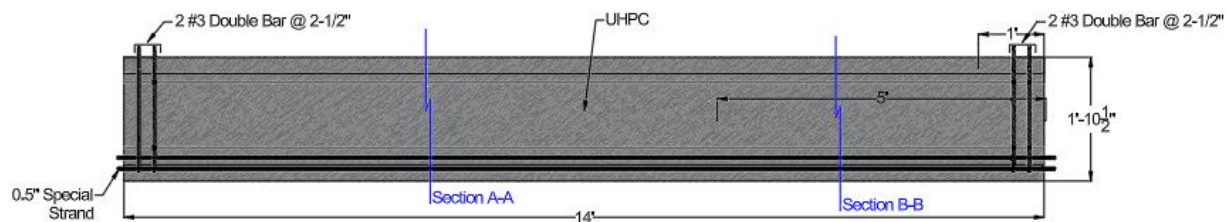


Figure 5. Side view of the full UHPC prestressed girders

The web in the end region of the UHPC girders was reduced similarly to that of the hybrid prestressed girders. Figure 6 presents the cross-sectional view of the full UHPC prestressed girders showing the prestressing strand locations.

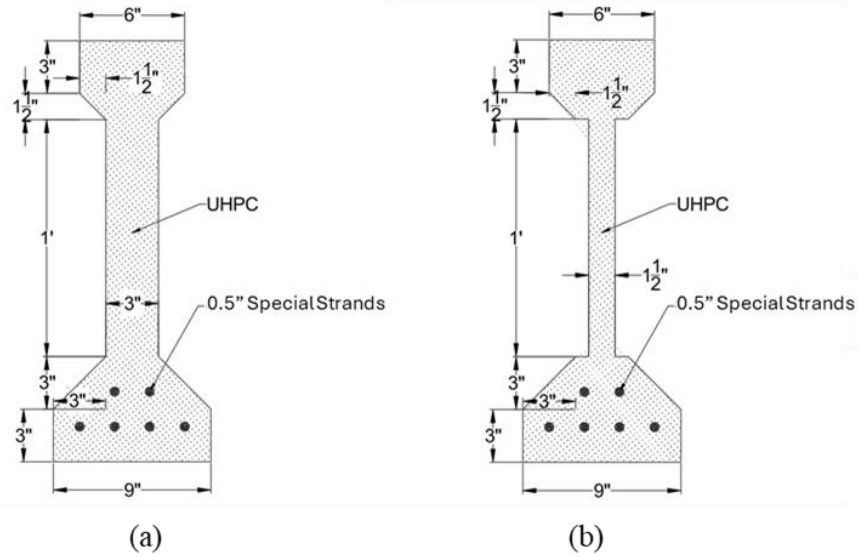


Figure 6. Cross sectional view of UHPC (a) half-scale AASHTO Type II girder and (b) end region

2.4. UHPC Concrete Shell Prestressed Girders

The cross-sectional design of the stay-in-place formwork (UHPC shell) prestressed girders was a 9-in. by 16-in. rectangular shape with a 1 in. shell thickness as depicted in Figure 7. This modification from the I-girder used for the other specimens was intended to simplify the construction of formwork for this proof of concept. The dimensions of the UHPC concrete shell prestressed girders were selected to provide a cross-section resulting in applied stresses approximately equal to those in the hybrid girder specimens. Figure 8 shows the tensile, compressive and allowable stresses of the prestressed girders at end regions of the UHPC stay-in-place formwork girder design for 180 ksi prestressing stress. The stay-in-place formwork girder design had the same number of strands and similar strand locations to the other specimens. Additionally, the length of this girder type was set at the same 14 ft used for the full UHPC girders.

The same SCC mix design used for the hybrid girders, shown in Table 4, was used to fill the UHPC concrete shell. The design of these girders did not include shear reinforcement but included bursting reinforcement at both ends of the girders designed in accordance with AASHTO section 5.9.4.4 (AASHTO 2020). The vertical sides of the UHPC shell were anticipated to provide required shear reinforcement. Figure 9 illustrates the side view of the stay-in-place formwork prestressed girders with bursting reinforcement.

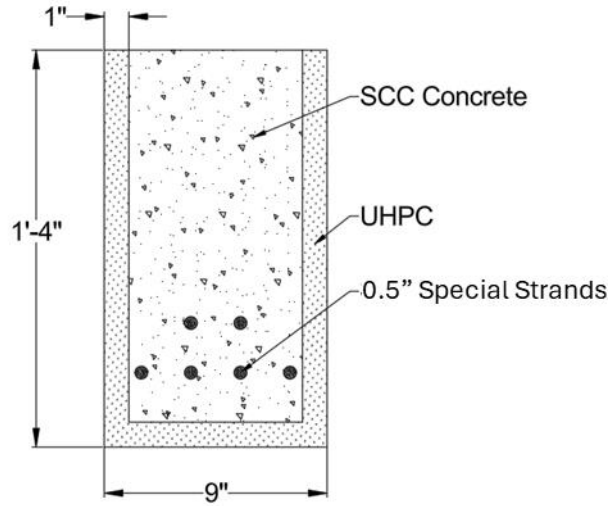


Figure 7. Cross-section view of the UHPC stay-in-place formwork shell prestressed girders

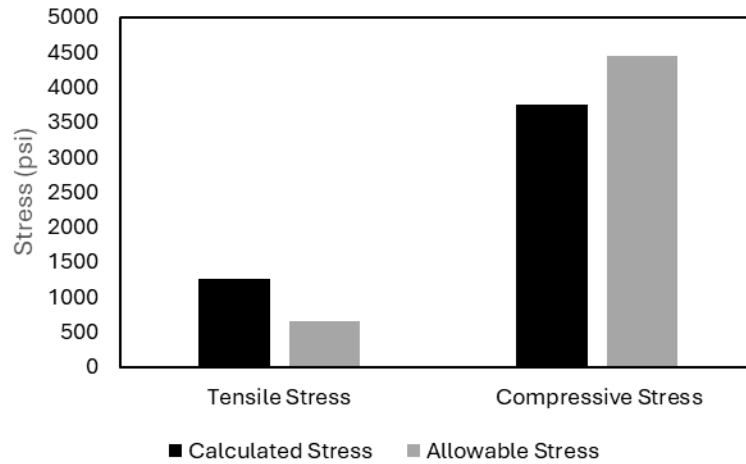


Figure 8. Tensile, compressive and allowable stresses at the end region of the UHPC shell specimen for a 180 ksi prestress

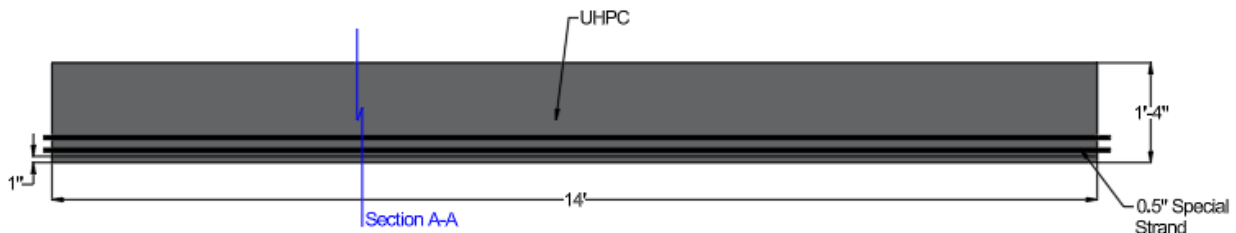


Figure 9. Side view of the UHPC stay-in-place formwork shell prestressed girders

Chapter 3. Prestressed Girders Construction

This section outlines the construction process of the prestressed girders and the placement of the instruments used for measuring prestress losses.

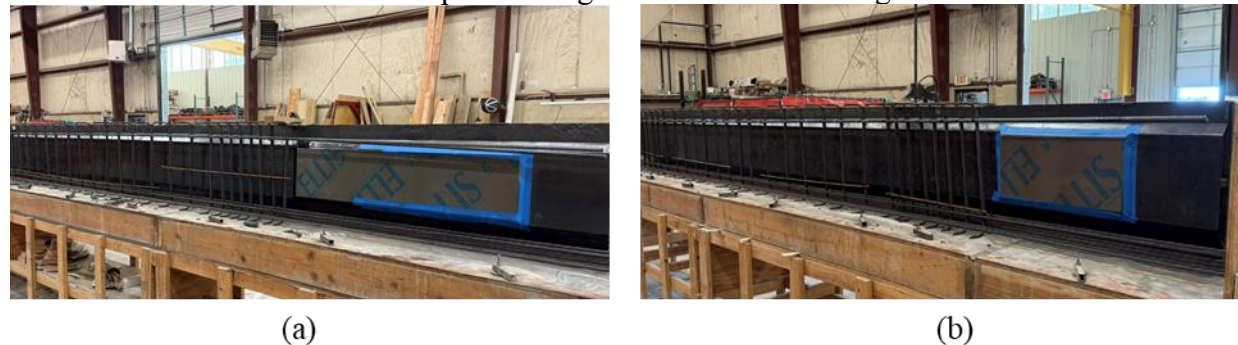
3.1. Hybrid UHPC Prestressed Girders

Five hybrid UHPC prestressed girders were constructed following the same procedure. Existing metal formwork was used to cast the hybrid UHPC prestressed girders. Wooden inserts were added to the formwork sides to create the reduced web section at the end regions as described in Section 2.2. Figure 10 shows one side of the formwork on the prestressing bed with the wooden web insert in place for the two different lengths of reduced web section tested.



Figure 10. Formwork side after placement of (a) 5 ft wooden web insert and (b) 3 ft wooden web insert

The reinforcement for the SCC section of the prestressed girder was placed after one side of the formwork was assembled on the prestressing bed based on the design described in Section 2.2.





Three vibrating wire strain gauges were placed at three separate locations along the length of the girders attached to the top two prestressing strands. These locations included 1 ft from the live end (defined as the end nearest to the end of the prestressing bed where the strands were tensioned), at midspan, and 1 ft from the dead end (defined as the end opposite the live end). The gauges were secured to the strands using metal rods and zip ties.

14



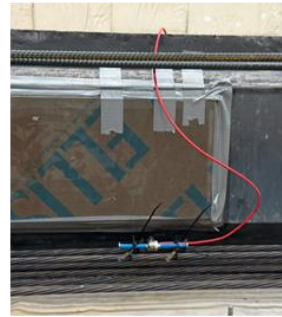
(a)



(b)



(c)



(d)

Figure 12. Layout of the vibrating wire strain gauges and their attachment to the top two strands including (a) overall layout, (b) close-up of gauge at the dead end, (c) close-up of gauge at midspan, and (d) close-up of gauge at the live end



Figure 13. Hybrid girder specimen layout on prestressing bed

After the vibrating wire strain gauges were placed, the other side of the formwork, end plates and dividers were placed as shown in Figure 14. The dividers were inserted at the anticipated interface between the SCC and UHPC to help control the flow of the two concrete types during casting. While the dividers did not block the entire width of the bottom flanges, they did block most of the top flange and web widths.



(a)



(b)



(c)

Figure 14. (a) Completed girder specimen formwork (b) Completed formwork end view and (c) SCC-UHPC divider in formwork



(a)



(b)

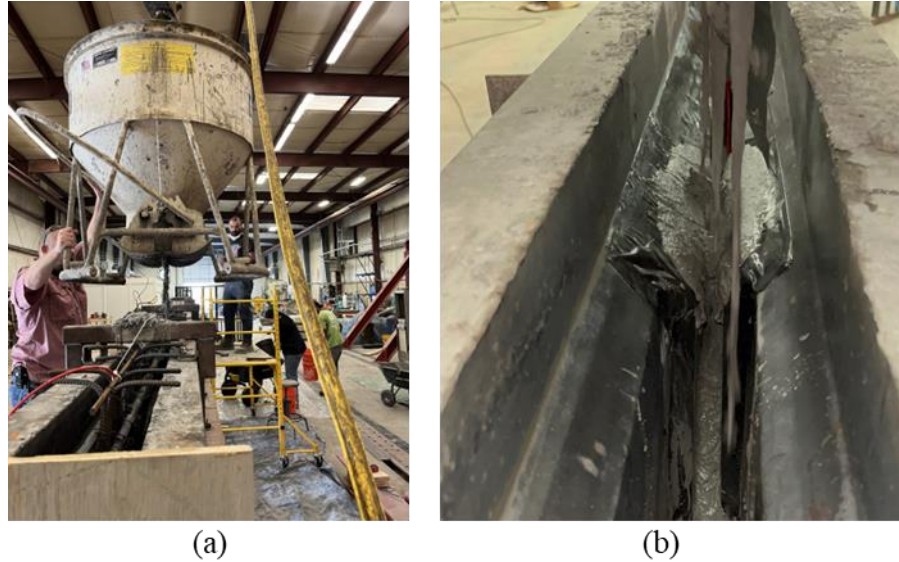


Figure 15(a) and

Figure 15(b) illustrate the casting process of the two concrete mixes. Both the SCC and UHPC were cast simultaneously. The SCC was mixed first since the SCC section required a larger volume than the UHPC section. The casting process began by pouring a portion of the SCC from the end opposite the UHPC section (dead end).

To facilitate the casting process and to achieve a better interface between the two concrete mixes, two individuals were responsible for casting the SCC, while two others were at the UHPC end to monitor the flow of the SCC coming toward the interface. As soon as the SCC flow was observed near the interface, the UHPC casting began using 5-gallon buckets filled with UHPC. Visual observations were made to control the flow of each mix and to maintain equal heights of both materials. The divider at the interface that helped regulate the flow rate of both mixes was removed once casting was completed up to the top of the girder's top flange. Figure 16 shows the interface after the divider was removed. It was noticed that some SCC flowed into the UHPC end during casting of the first beam set, as demonstrated in Figure 17. Since the girders in Figure 17 were the first set of the hybrid girders cast, more considerations were taken to better evaluate and control the flow rate of the SCC and to improve the quality of the interface for subsequent specimens.



(a)



(b)

Figure 15. (a) SCC placement and (b) UHPC placement at the reduced web section



Figure 16. UHPC-SCC interface after casting



Figure 17. Completed hybrid specimen showing intermixing of SCC and UHPC

3.2. Full UHPC Prestressed Girders

Three full UHPC prestressed girders were cast following a procedure similar to that used for the hybrid prestressed girders for construction and instrumentation. No shear reinforcement was added; only bursting reinforcement was added at the end regions designed in accordance with AASHTO section 5.9.4.4 (AASHTO 2020). The girders were 14 ft long instead of the 18 ft used for the hybrid girders to reduce the required volume of material and since the development length required for UHPC compared to SCC is less.

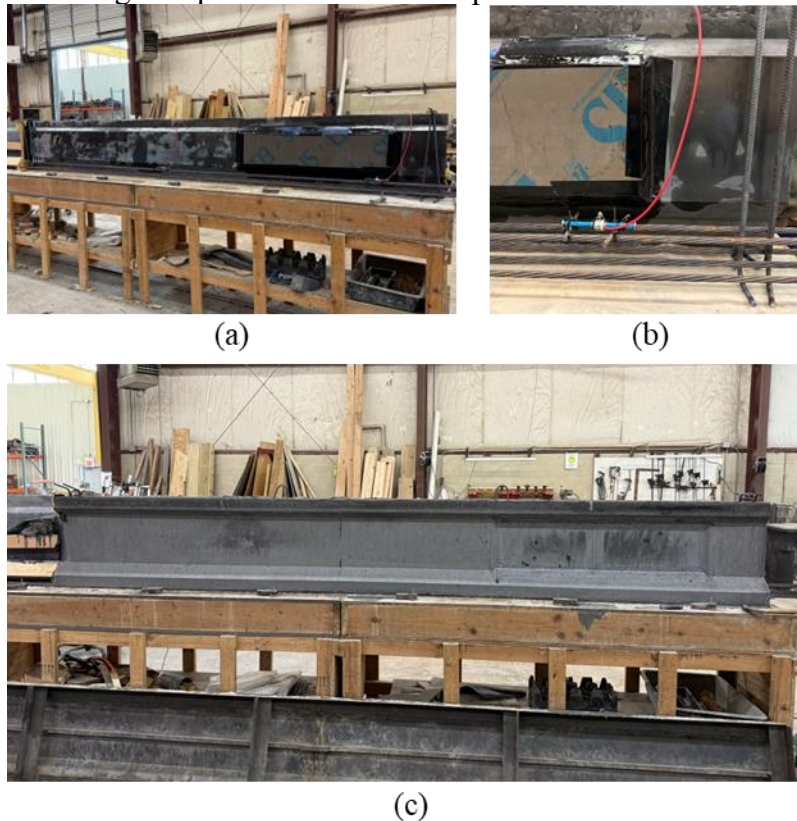


Figure 18 shows the formwork of a UHPC prestressed girder and the complete specimen after prestress release.

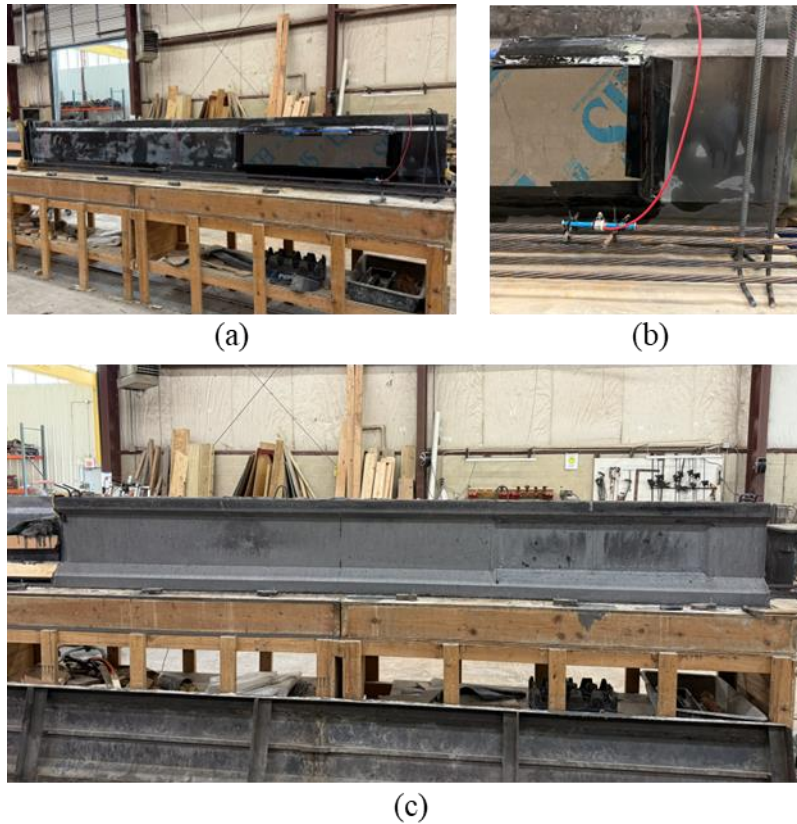


Figure 18. (a) Formwork side with UHPC girder reinforcement in place (b) vibrating wire strain gauge and end region reinforcement at reduced web section and (c) complete UHPC prestressed girder specimen after release

3.3. UHPC Concrete Shell Prestressed Girders

One stay-in-place formwork prestressed girder was constructed and cast. Before finalizing the design of the specimen, small trial specimens were cast to evaluate the bond strength between the UHPC and SCC. Two types of interface were evaluated for these trial specimens: smooth and grooved. The reason for casting these trial specimens was to investigate the bond strength as UHPC was cast first and the prestress force would have to transfer from the SCC infill to the

UHPC formwork shell through the bond between the two materials. The casting order is important because UHPC is typically cast over the conventional concrete. Foam inserts and existing 8 in. by 8 in. by 30 in. formwork were utilized to create the UHPC shell stay-in-place formwork as demonstrated in



(a)



(b)



(c)

Figure 19.



(a)



(b)



(c)

Figure 19. (a) 8 in. by 8 in. by 30 in. formwork (b) smooth formwork insert and (c) grooved formwork insert

The UHPC shell was designed to be 1 in. thick.

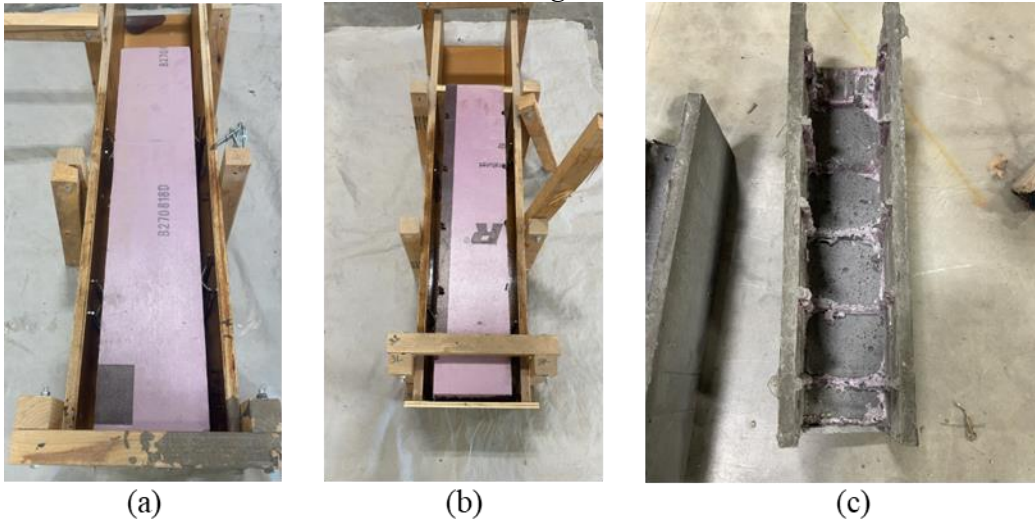


Figure 20(a) and

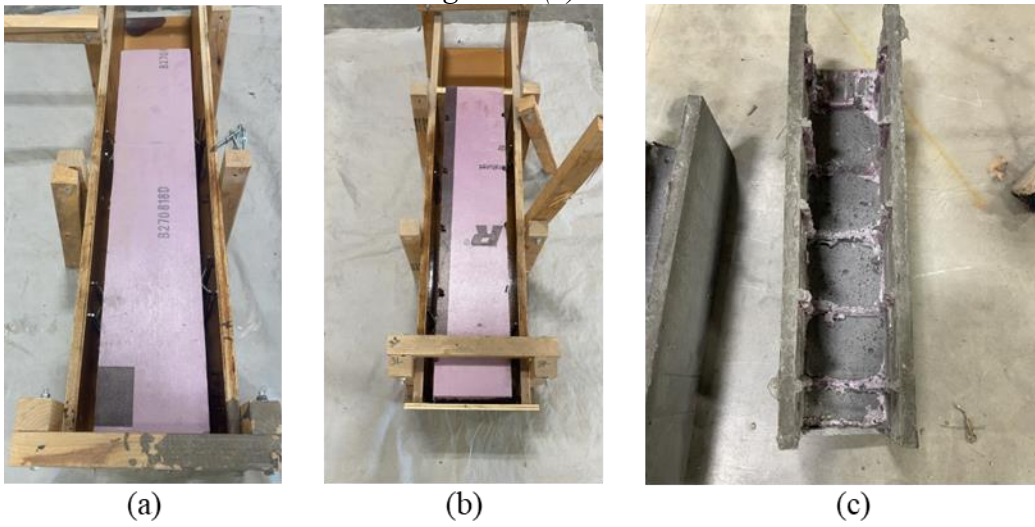


Figure 20(b) show the foam inserts inside the formwork, and

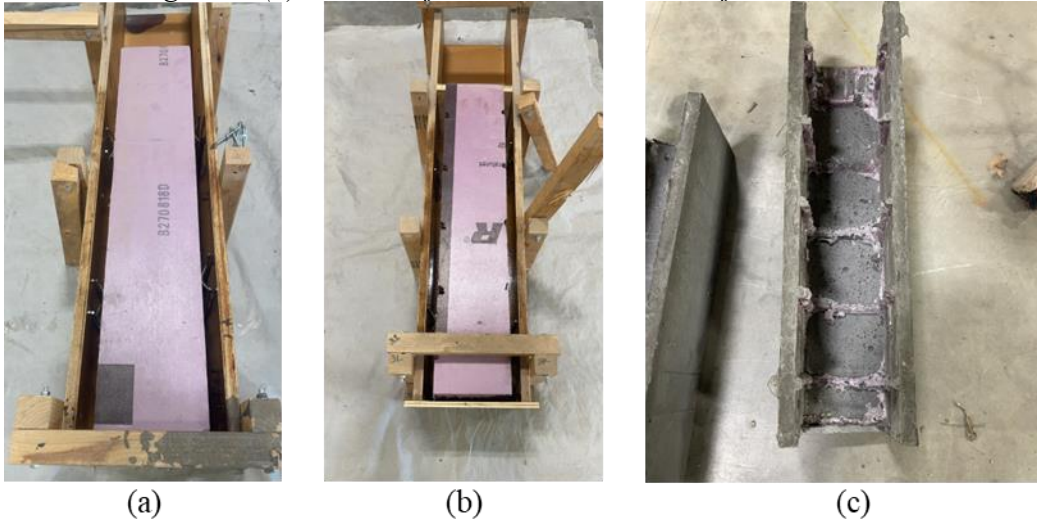


Figure 20(c) shows the shell after UHPC was cast and formwork was removed. The shells were cast using the UHPC mix design described in Table 1.



Figure 21 shows a completed shell specimen after casting SCC.

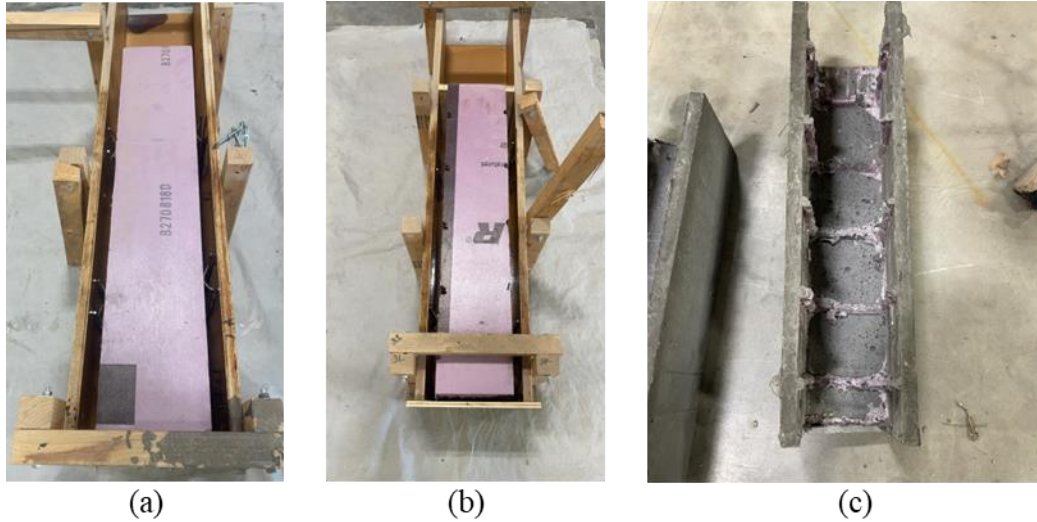


Figure 20. (a) Formwork for smooth interface shell (b) formwork for grooved interface shell and (c) completed grooved interface shell



Figure 21. (a) Completed UHPC shell specimens and (b) end view of UHPC shell specimen

After successfully casting the trial specimens, a 14 ft long large-scale UHPC shell was constructed based on the design presented in Section 2.4. The shell formwork consisted of an outer U-shaped form and an inner U-shaped formwork to achieve the required shell dimensions as shown in Figure 22. Vertical braces were inserted inside the inner formwork to provide support and prevent bowing of the plywood during casting. Rebar chairs were placed under the bottom of the inner formwork to maintain the required gap of 1 in. As this was the first large-scale concrete shell specimen the research team had constructed, the construction process was planned to be as simple as possible to ensure practicality.

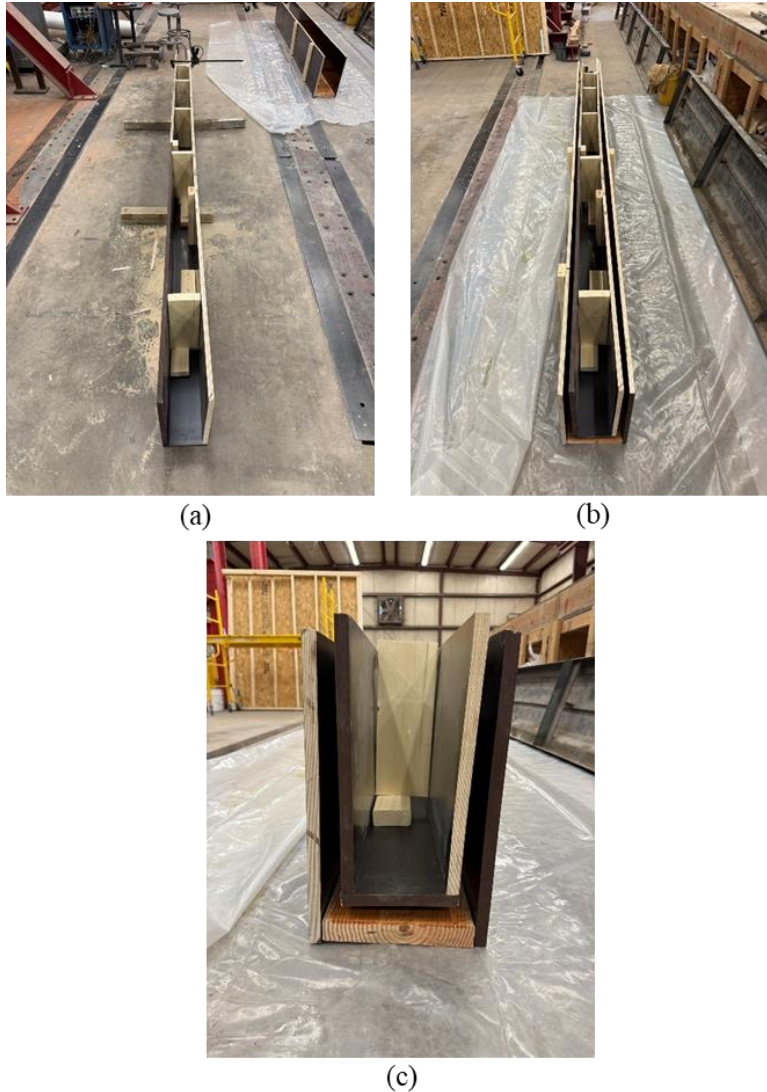


Figure 22. (a) Inner formwork for the UHPC shell, (b) inner formwork inside the outer formwork, and (c) end view of concrete shell formwork

End plates were placed on each end of the formwork, and ratchet straps were used to hold all the pieces together and ensure tightness of the formwork. UHPC was cast by pouring 5-gallon buckets filled with UHPC into the gap between the outer and inner formwork. Figure 23 and Figure 24 present the completed formwork during casting and the shell after removal of formwork, respectively. On one side of the shell, the thickness of the bottom section was approximately 2 in. instead of 1 in. due to an uplift issue that occurred during the casting process.

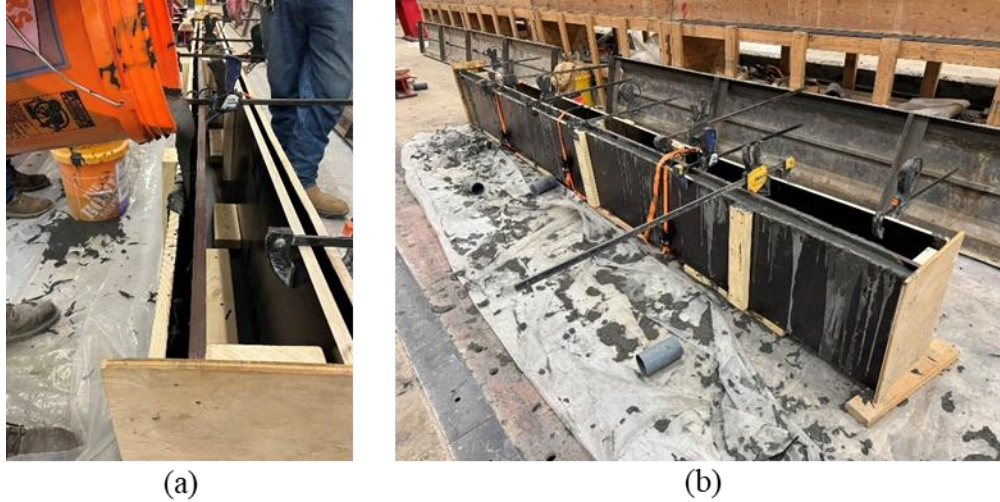


Figure 23. (a) UHPC poured into the gap between the inner and outer formwork and (b) completed concrete shell formwork after casting

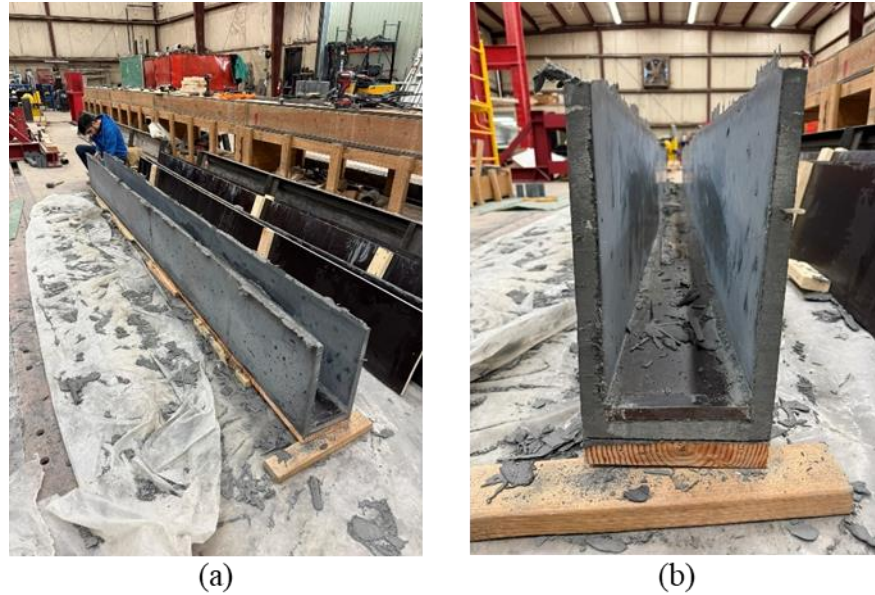


Figure 24. Completed UHPC shell (a) overall view and (b) end view

Due to variation in the thickness of the shell caused by formwork deformation during construction, the original design with 6 0.5 in. special strands did not fit in the shell. The design of the specimen was modified to accommodate the change in the shell's dimensions. Four 0.6 in. strands were used instead of 6 0.5 in. special strands in order to meet the required cover between the sides of the shell and strands. The modified design was selected after matching the compressive stresses at the end regions with the end region stresses of the original design. The prestressing stress was increased to 200 ksi to obtain the required stresses at end regions. Table 6 shows the stresses at end regions using 6 0.5 in. special strands with 180 ksi prestressing stress and four 0.6 in. strands with approximately 200 ksi prestressing stress.

Table 6. Comparison of stresses between original and modified designs of the concrete shell specimen

Stress	Original Design Stress (ksi)	Modified Design Stress (ksi)
End region Tensile Stress	1.25	1.21
End region Compressive Stress	3.75	3.62
Midspan Tensile Stress	1.1	1.06
Midspan Compressive Stress	3.30	3.47

No surface preparation or further treatment was performed on the shell after removal of formwork and before infill casting. The UHPC shell was placed on the prestressing bed to prepare for casting the concrete infill. Since the shell was 2 in. thick at one end, the prestressing bed was adjusted to maintain a 2 in. spacing from the bottom of the bed to the center of the first layer of strands. The four 0.6 in. strands were prestressed to 200 ksi to approximately match the end region stresses of the other prestressed girders. The SCC mix design described in Table 3 was used as the concrete infill for the UHPC shell and was placed in a similar fashion to the hybrid girders. Figure 25 presents the stay-in-place formwork prestressed girder before casting, during casting, and after prestress release.



Figure 25. UHPC shell prestressed girder (a) before casting, (b) during casting, and (c) after completion

3.4 Girder Strain Monitoring

The strain in all girders was measured using the vibrating wire strain gauges plugged into a data logger and was read using the Geokon LogView program. Strain measurements were collected every minute for the first 6 days after concrete was cast. Girders were moved to their designated area after prestress release. Since two prestressed girders were cast for each concrete pour and both girders could not be moved at the same time, strain measurement was paused during relocating the girders to their permanent area to avoid any complications with the instruments. After that, strain measurements were collected every 5 minutes for 2 months then every 15 minutes until the end of the prestress loss measurements.

Chapter 4. Results

4.1 Concrete Compressive Strength

Figure 26 and Figure 27 show the compressive strength of concrete used for each girder at prestress release and at 28 days, respectively. The average SCC compressive strength was 7,400 psi at release and 9,500 psi at 28 days. The average UHPC compressive strength was 10,000 psi at release and 18,500 psi at 28 days.

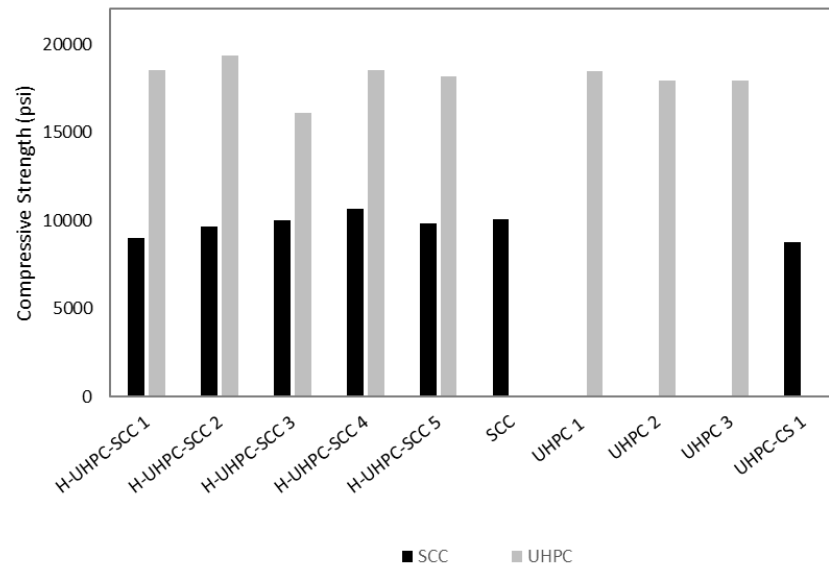


Figure 26. Compressive strength of prestressed girder concretes at the time of prestress release

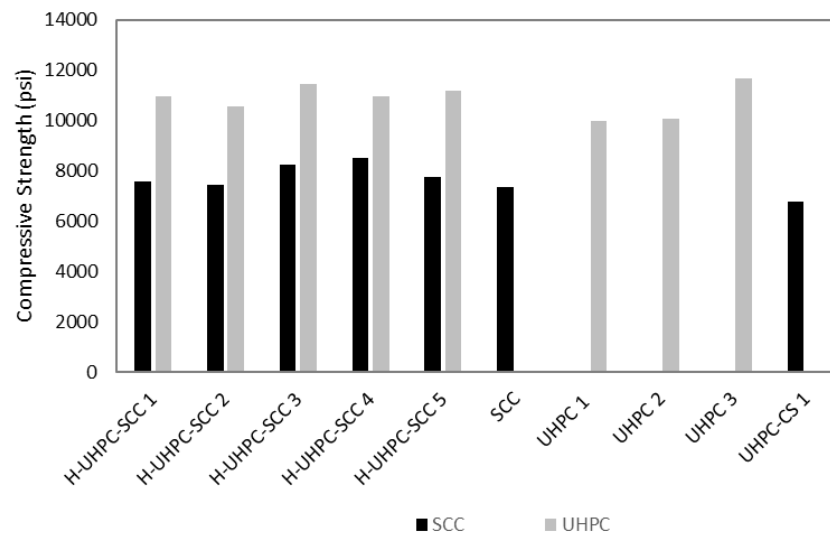


Figure 27. Compressive strength of prestressed girder concretes at 28 days

4.2 Concrete Compressive Stress

Figure 28 presents the compressive stresses determined from the measured strains at both ends of the prestressed girders as well as the allowable stress at release specified by AASHTO LRFD

based on the SCC compressive strength. At each UHPC end, the compressive stress was calculated using the measured strain from the vibrating wire strain gauge and UHPC modulus of elasticity calculated using the prediction proposed by Russell and Graybeal (38). Similarly, the compressive stress for each SCC end was determined from the measured strain and modulus of elasticity calculated using the AASHTO LRFD equation (33).

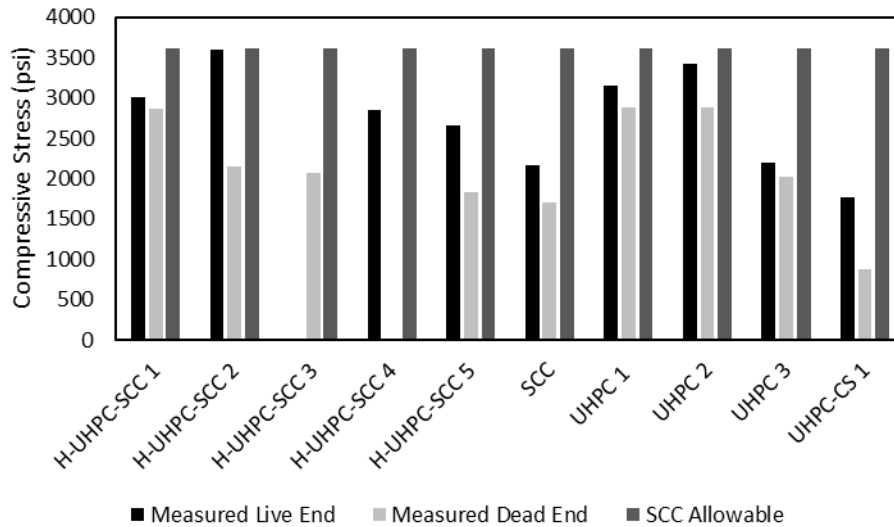


Figure 28. Compressive stress at the end regions of the prestressed girders

All the compressive stresses determined from the measured strains were within the stress limit determined for the SCC portion, as shown in Figure 28. However, the UHPC end (live end) of all the hybrid prestressed girders exhibited a larger compressive strain and a higher resulting compressive stress than the full SCC prestressed girder. Additionally, the UHPC ends of the hybrid prestressed girders also exhibited higher compressive strains and resulting stress than their corresponding SCC ends. This indicates that the prestress transfer length is shorter in the UHPC compared to the SCC and a larger percentage of the force was transferred at the gauge location. Although the compressive stress was higher at the UHPC ends, no cracking was observed at those locations. On the other hand, the SCC end region had small cracks that were observed in the bottom flange. This shows that the UHPC was better able to withstand high stress without additional reinforcement in the end region.

The full UHPC girders had measured compressive stresses less than the limits for SCC, but larger values were measured at the live ends. Specimens UHPC 1 and UHPC 2 exhibited cracks in the top of the beam section along the length that could be attributed to the high design tension stresses at release and lack of mild steel reinforcement in the top of these sections. Specimen UHPC 3 exhibited lower stresses at both end regions compared to UHPC 1 and UHPC 2 and no cracking appeared at the top flange for UHPC 3. This could be due to the addition of top mild reinforcement in UHPC 3 similar to what was provided in the hybrid girders. Specimen UHPC-CS 1 exhibited low compressive stresses compared to the other girders and cracks at the interface between the shell and concrete infill were observed, specifically at the live end. The cracks were smaller closer to the dead end of the specimen. Figure 29, Figure 30 and Figure 31 show the end regions of specimens H-UHPC-SCC 5, SCC, and UHPC-CS 1, respectively.



(a)



(b)

Figure 29. H-UHPC-SCC 5 (a) live end and (b) dead end after 150 days from after prestress release



(a)



(b)

Figure 30. UHPC-CS (a) live end and (b) dead end after 150 days from after prestress release

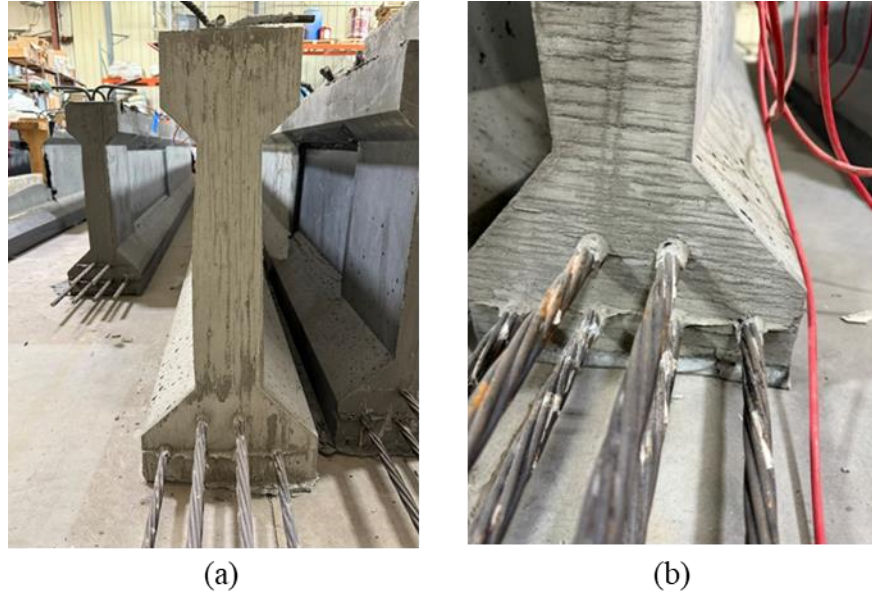


Figure 31. SCC (a) live end and (b) dead end after 150 days from after prestress release

4.3 Immediate Prestress Losses

Figure 32 presents the measured immediate elastic shortening losses for each girder at midspan compared to the elastic shortening losses calculated according to the AASHTO LRFD refined method (33). The measured elastic shortening was determined from the measured strain immediately before and after prestress release done two days after casting. For all the specimens, the calculated elastic shortening loss was less than the measured values, except for specimen H-UHPC-SCC 2 where the measured losses were similar to the calculated value. Specimens H-UHPC-SCC 3, H-UHPC-SCC 4, H-UHPC-SCC 5, and SCC had similar immediate prestress losses.

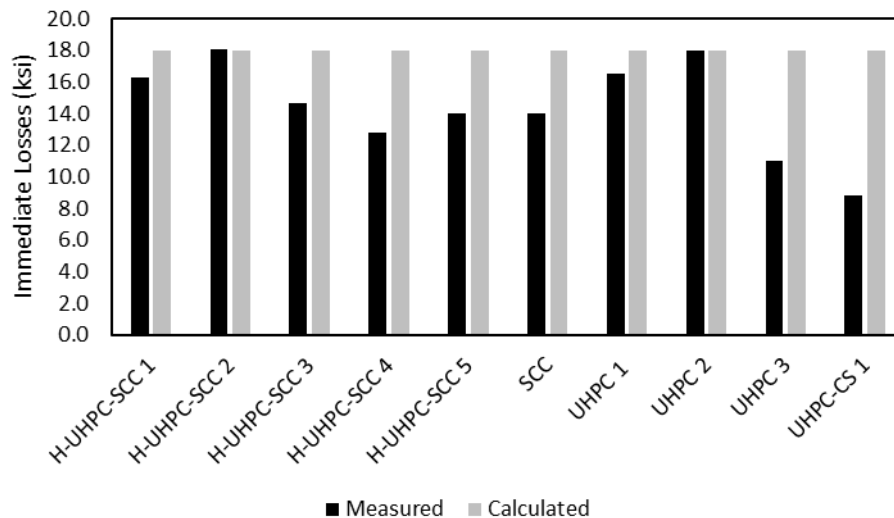


Figure 32. Comparison of measured and calculated elastic shortening at midspan for all girder specimens

The prestress loss behavior was further analyzed by investigating the trend of prestress stress transfer along the girder length. Figure 33 presents the measured elastic shortening at the end regions and midspan for all specimens. All hybrid girders followed the same trend. For each of these girders the UHPC end region and midspan had similar elastic shortening losses, whereas the SCC end region had a lower value. The values of the elastic shortening correspond to the high compressive stress and strain at the UHPC end region and the lower compressive strain and stress at the SCC end region. This difference is attributed to the location of the strain gauge relative to the prestress transfer length and the variation of that length with material.

Specimens UHPC 1, UHPC 2 and UHPC 3 had a different trend compared to the hybrid and SCC girders. The UHPC girders exhibited similar elastic shortening at the live end, midspan, and dead end. This suggests that the compressive forces were near uniform along the entire length of the girder. In contrast, the SCC girder exhibited lower elastic shortening at the end regions compared to all other girders. This corresponds to the smaller measured compressive strains at the end regions which aligns with the lower compressive forces at the gauge locations within the prestress transfer length.

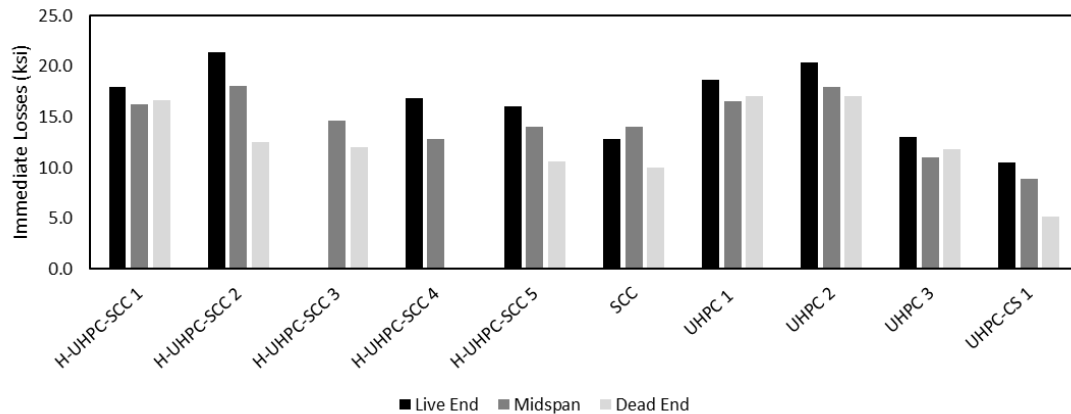


Figure 33. Comparison of measured elastic shortening at midspan and the end regions for all girders

4.4 Time-dependent Prestress Losses

Figure 34 presents the measured and calculated time-dependent losses at midspan 150 days after prestress release for all specimens except UHPC 3 and CS-UHPC 1, which have not reached 150 days. The measured prestress losses were similar to the calculated values obtained from the AASHTO refined method for all specimens except H-UHPC-SCC 2. This could be due to material variability since the girders were cast from different concrete batches. The measured prestress losses of the hybrid girders at midspan were approximately equal to full SCC girder losses, suggesting similar behavior between the hybrid and full SCC girders.

Cracks were observed at the top flange of specimens UHPC 1 and UHPC 2 after prestress release. The cracks extended from the top flange to the web of both girders near midspan whereas the cracks were within the top flange near the live and dead ends as shown in Figure 35. It should be noted that no top reinforcing steel was included in these beams, which likely controlled similar cracking in the other girders. Measured prestress losses for girder UHPC 1 were smaller than the calculated values, but girder UHPC 2 exhibited higher prestress losses than the calculated values.

This could be due to the difference in the steel fiber percentage in the UHPC mix design since UHPC 1 had 2% fiber by volume whereas UHPC 2 had 1% fiber by volume. A smaller fiber percentage corresponds to less tensile stress and cracking resistance. The presence of cracks contributed to more creep development over time in both girders.

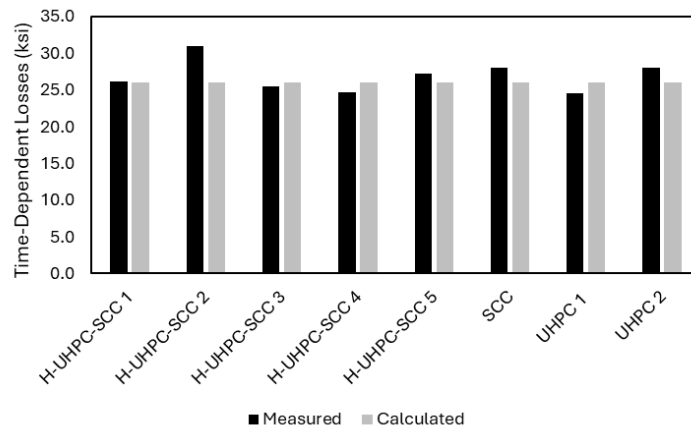


Figure 34. Comparison of measured creep and shrinkage losses at midspan 150 days after prestress release

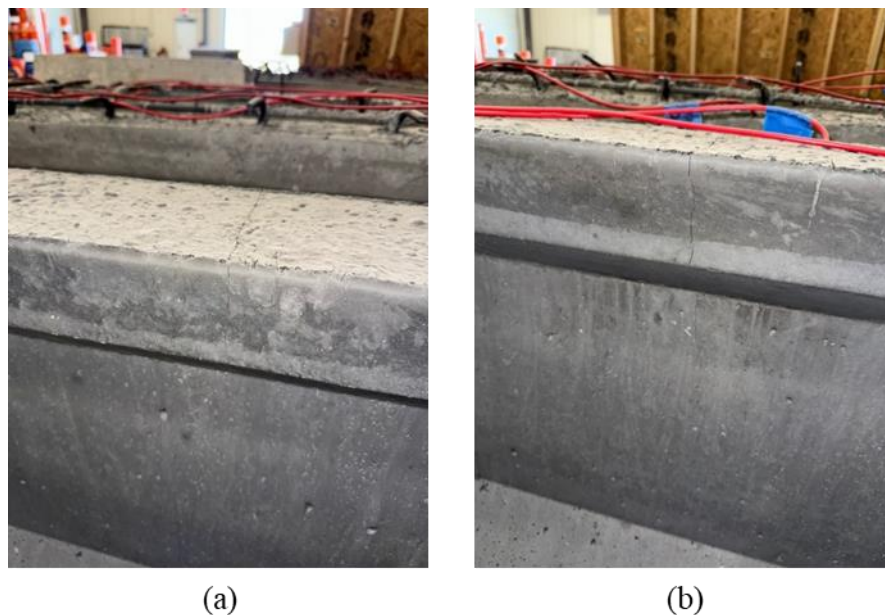


Figure 35. Cracks at the top flange of girder specimens UHPC 1 and UHPC 2 at (a) 4 ft from live end and (b) near midspan

As shown in Figure 36, the midspan section of the hybrid girders exhibited similar time-dependent prestress losses to those measured for the SCC girder. This indicates that the composite behavior between the UHPC and SCC in the hybrid design did not have a significant effect in the long-term prestress losses at midspan. In terms of the long-term prestress losses at end regions, the specimens demonstrated trends similar to those observed for the immediate prestress losses at the end regions. For girders UHPC 1 and UHPC 2, higher prestress losses were observed at the live end region than

midspan, suggesting a shorter transfer length allowed the prestress force to develop more uniformly along the girder.

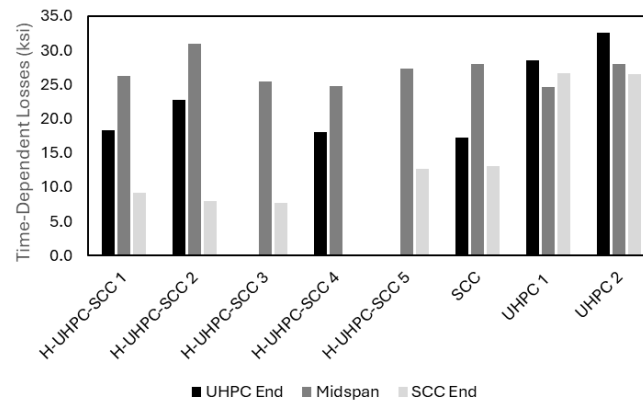


Figure 36. Comparison of measured creep and shrinkage losses at midspan and the end regions 150 days after prestress release

Chapter 5. Discussion

This section presents comparison between the prestressed girders in terms of overall behavior over time. The overall behavior for all the prestressed girders is presented in Appendix A.

5.1 Girders H-UHPC-SCC 1 and SCC

The overall prestress losses behavior for the H-UHPC-SCC 1 and full SCC girders was compared at the live end region and midspan. Both girders were prestressed to 180 ksi, and the hybrid girder had a 5 ft overall UHPC section. As shown in Figure 37, The UHPC end region of the hybrid girder had a shorter transfer length putting the end region under greater stress at the gauge location. The H-UHPC-SCC 1 curve shows greater losses over time compared to the SCC live end, which suggests a high compressive stress resulting in more creep and potentially more shrinkage occurring over time.

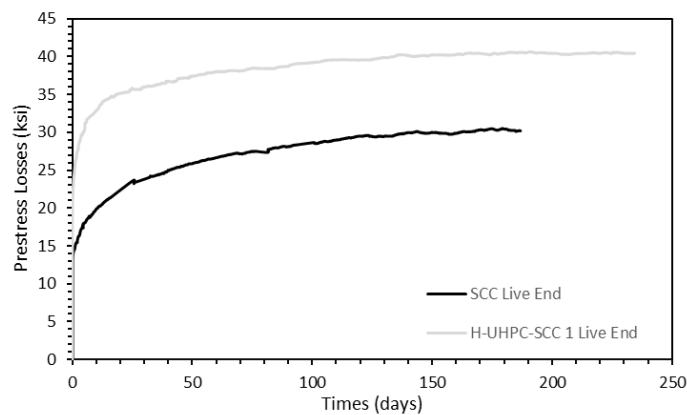


Figure 37. Measured prestress losses over time for the H-UHPC-SCC 1 and SCC girder at the live end

The prestress losses at midspan rapidly increased in the hybrid girder in the first 20 days after prestress release, while the prestress losses for the full SCC girder increased more gradually, reaching the losses of the hybrid girder after approximately 60 days as demonstrated in Figure 38. This could be indicative of different rates of creep development. The hybrid girder behavior suggests a faster early-age creep or shrinkage at midspan potentially due to the high compressive stress transfer from the UHPC end. The SCC girder behavior shows a steadier increase indicating slower but more sustained creep and shrinkage over time.

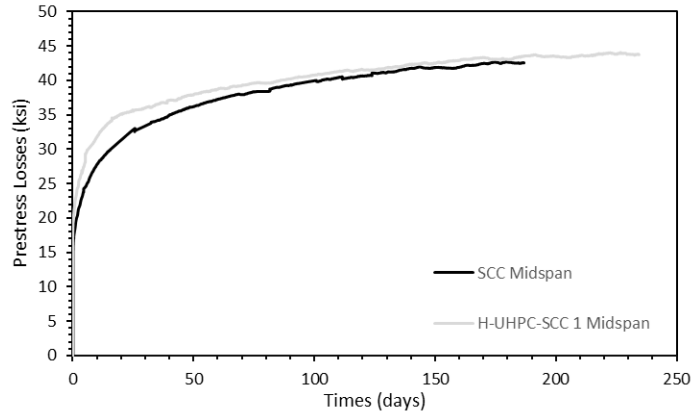


Figure 38. Measured prestress losses over time for specimen H-UHPC-SCC 1 and the SCC girder at midspan

5.2 Girders H-UHPC-SCC 1 and UHPC 1

Figure 39(a) and Figure 39(b) present the overall prestress loss behavior for the H-UHPC-SCC 1 and UHPC 1 girders. Both girders were prestressed to 180 ksi and had a 5 ft overall UHPC section. Both girders exhibited similar trends of prestress losses at their live end region and midspan. However, the UHPC 1 losses at midspan were higher over the first 20 days. The prestress losses were also higher in the UHPC 1 live end overall. The higher compressive force transferred at the live end likely contributed to these behaviors, but they also could be due to the cracking that was observed on the top flange of the UHPC girders at multiple locations and reduced the effective moment of inertia.

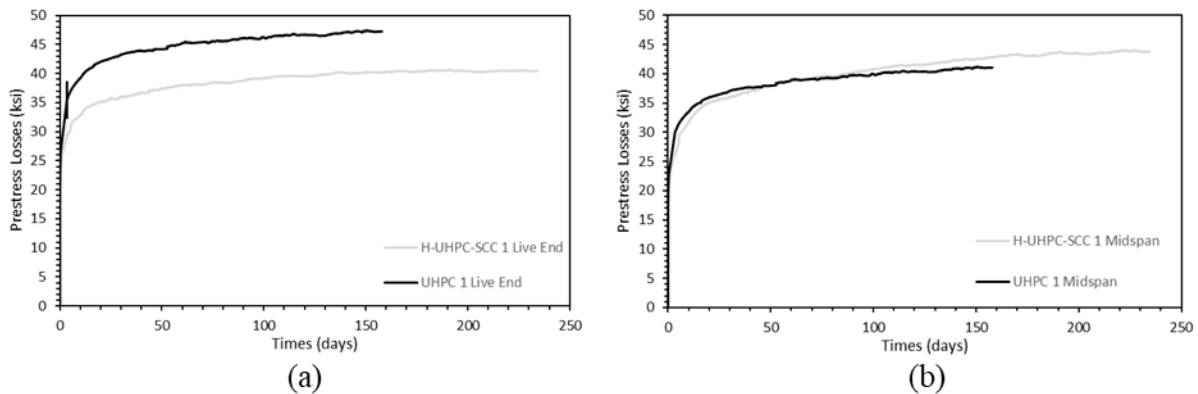


Figure 39. Measured prestress losses over time for girders H-UHPC-SCC 1 and UHPC 1 at (a) the live end and (b) midspan

5.3 Girders H-UHPC-SCC 1, H-UHPC-SCC 3 and H-UHPC-SCC 4

The overall prestress losses behavior for girders H-UHPC-SCC 1, H-UHPC-SCC 3, and H-UHPC-SCC 4 is presented in Figure 40. There is a gap in the data for H-UHPC-SCC 3 due to an error in the vibrating wire gauge at the live end. Girders H-UHPC-SCC 3 and H-UHPC-SCC 4 were prestressed to 202.5 ksi but had 5 ft and 3 ft overall UHPC sections, respectively. Girder H-UHPC-SCC 1 was prestressed to 180 ksi with a 5 ft overall UHPC section. Unexpectedly, the midspan and live end losses over time for girder H-UHPC-SCC 3 and H-UHPC-SCC 4 were less than for

H-UHPC-SCC 1 even though more prestressing force was applied to those two girders. H-UHPC-SCC 3 and H-UHPC-SCC 4 exhibited 40 and 37.5 ksi prestress losses, whereas H-UHPC-SCC 1 exhibited 43 ksi prestress losses at 150 days. This potentially could be due to better stress distribution or simply concrete variability since the girders were not cast from the same concrete batch. However, the trend was similar where the prestress losses at the dead end region were less than at midspan for H-UHPC-SCC 1 and H-UHPC-SCC 3.

The length of the overall UHPC section did not appear to have an effect on the overall behavior of the girders. The compressive stress at the UHPC end region and the measured prestress losses were similar in all specimens regardless of the UHPC section length.

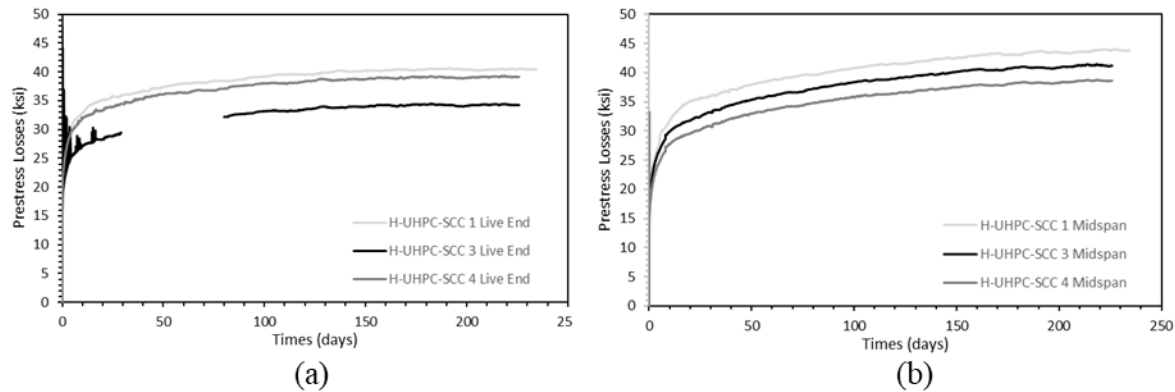


Figure 40. Measured prestress losses over time for the H-UHPC-SCC 1, H-UHPC-SCC 3, and H-UHPC-SCC 4 girders at (a) live end and (b) midspan

5.4 Girders UHPC 1, UHPC 2, and UHPC 3

The overall behavior of the three UHPC prestressed girders is presented in

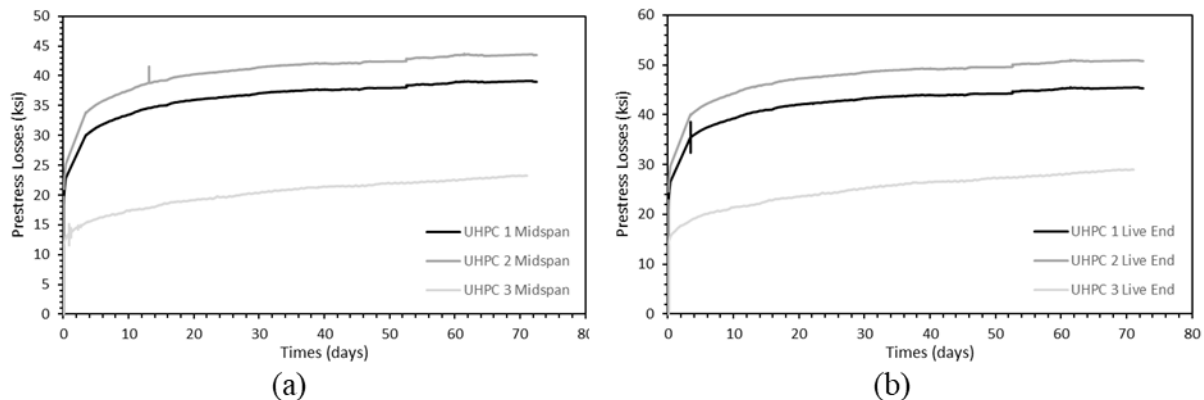


Figure 41. UHPC 1 and UHPC 2 were prestressed to 180 ksi with no top steel reinforcement, however, UHPC 3 included top steel reinforcement with the same prestressing stress as UHPC 1 and UHPC 2. The total prestress losses for UHPC 3 were less than for UHPC 1 and UHPC 2. UHPC 3 exhibited 22 ksi prestress losses at 72 days, whereas UHPC 1 and UHPC 2 exhibited more than 35 ksi prestress losses at 72 days. The compressive stress at the live end for UHPC 3 was also lower than the stress for UHPC 1 and UHPC 2. The difference in behavior could

potentially be due to the presence of top reinforcement in UHPC 3 which helped the girder to maintain its cross section without the top cracks as observed in UHPC 1 and UHPC 3.

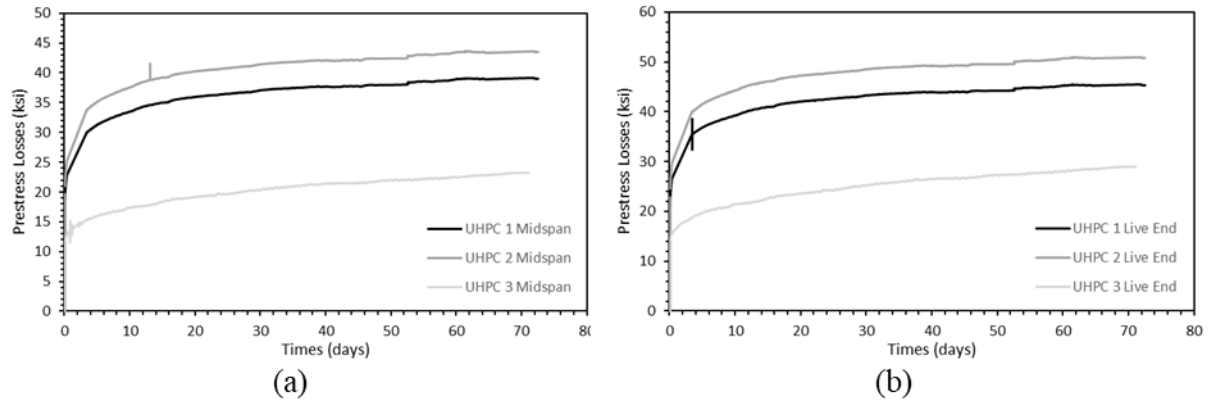


Figure 41. Measured prestress losses over time for the UHPC 1, UHPC 2 and UHPC 3 girders at (a) live end and (b) midspan

5.5 Girders H-UHPC-SCC 1 and UHPC-CS 1

The overall prestress losses behavior for the H-UHPC-SCC 1 and UHPC-CS 1 girders was compared at the live end region and midspan as presented in

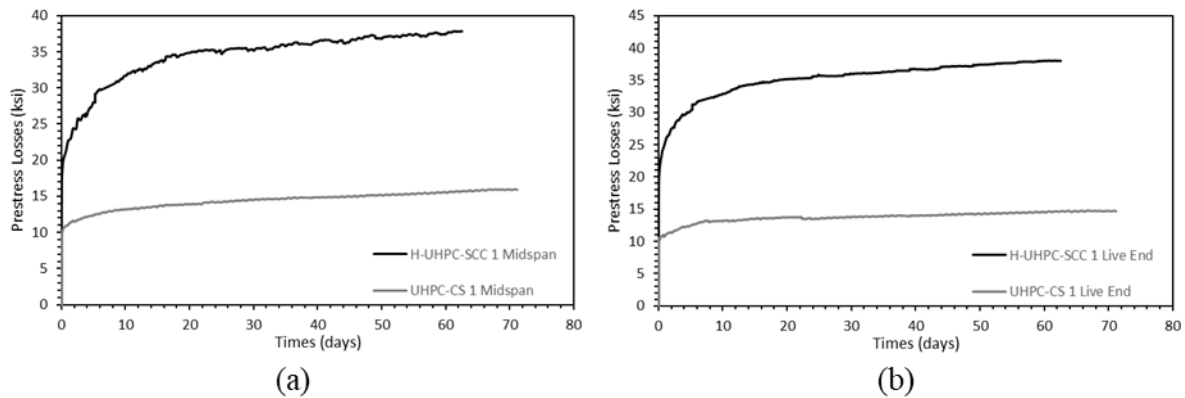


Figure 42. Both girders were prestressed to 180 ksi. The prestress losses for the UHPC-CS 1 girder were 16 ksi, whereas the losses were 39 ksi for H-UHPC-SCC 1 at 70 days. The difference in measured losses could be due to the lower transferred force in the UHPC-CS 1 girder compared to H-UHPC SCC 1, which was caused by the debonding that occurred in the interface between the SCC and UHPC concretes. More data collected for the UHPC-CS 1 girder over time will help understand the behavior of the girder in terms of time-dependent prestress losses.

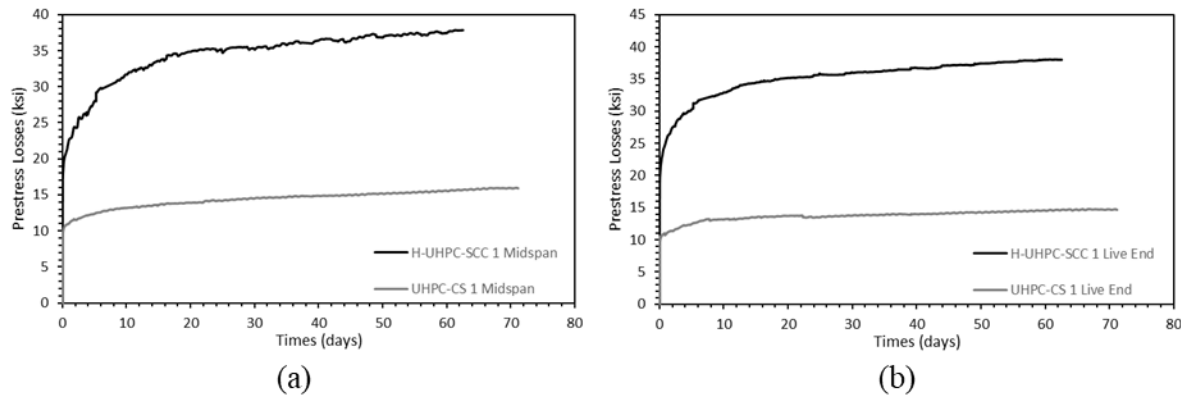


Figure 42. Measured prestress losses over time for H-UHPC-SCC 1 and UHPC-CS 1 girders at (a) live end and (b) midspan

Chapter 6. Summary, Conclusions, and Future Work

Five approximately half-scale AASHTO Type-II hybrid prestressed girders with the Bi-fluid interface were successfully cast without any major construction-related issues. The use of a wooden divider at the interface between UHPC and SCC helped to control the flow rate of the UHPC and SCC and maintain the two materials separated until the casting process was done. Three full UHPC girders, one SCC girder, and one stay-in-place formwork prestressed girder were also successfully cast to compare their behavior with the hybrid prestressed girders.

The UHPC end regions for all the hybrid prestressed girders followed the same trend, with higher compressive stress compared to the SCC end regions. The high stress at the UHPC ends did not induce any observed cracks after 150 days, however, some cracks were observed at the SCC end regions for some of the hybrid prestressed girders and the SCC girder. The time-dependent (creep and shrinkage) prestress losses behavior of the hybrid prestressed girders was similar to that of the SCC prestressed girder and full UHPC prestressed girders, indicating that the hybrid design did not appear to have an impact on the prestress losses at midspan. The length of the overall UHPC section in the hybrid prestressed girder did not have an effect on prestress loss behavior at midspan and the UHPC durability to withstand high compressive stresses at the end region. This suggests that for the stress conditions tested in this research the UHPC end can be reduced to 3 ft at the end regions of the hybrid prestressed girders without compromising transfer of the prestress due to the short prestress transfer length in UHPC.

The full UHPC prestressed girders followed the same trend in the behavior of prestress losses. However, the UHPC 1 and UHPC 2 prestressed girders exhibited higher stresses at the end regions and midspan compared to the UHPC 3 prestressed girder. This could potentially be due to the presence of top reinforcement in UHPC 3 which helped the girder to maintain its cross section without the top cracks observed in specimens UHPC 1 and UHPC 3.

The stay-in-place UHPC formwork shell trial specimens showed good bonding between UHPC and SCC for both interface conditions. However, the large-scale stay-in-place concrete

shell prestressed girder had debonding cracks at the interface between the UHPC and SCC after prestress release. No surface preparation was done on the UHPC shell before casting the infill, which created a worst case scenario. Additionally, variations in the UHPC shell caused by formwork deformation during casting resulted in a design change that may have impacted behavior.

Further work should be done including collecting more data over time, shear testing and casting more UHPC and hybrid specimens with higher prestressing stress to investigate the measured prestress losses and to evaluate different end region detailing. An additional set of full UHPC girders prestressed to 202.5 ksi should be cast to examine potential difference in prestress loss behavior between full UHPC and hybrid girders for different levels of prestressing. Deck placement will be done on all the completed girders, then they will be tested in shear to evaluate the performance and continuity of the composite section. The shear testing will be conducted after the required time-dependent prestress losses measurements are completed. Additionally, another stay-in-place concrete shell prestressed girder should be cast with more accurate shell dimensions to ensure the right correct concrete cover between the strands and the UHPC shell. Having insufficient cover might have affected the prestress transfer between the UHPC and SCC.

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Appendix

The figures in this Appendix present the prestress losses measured over time for each of the girder specimens.

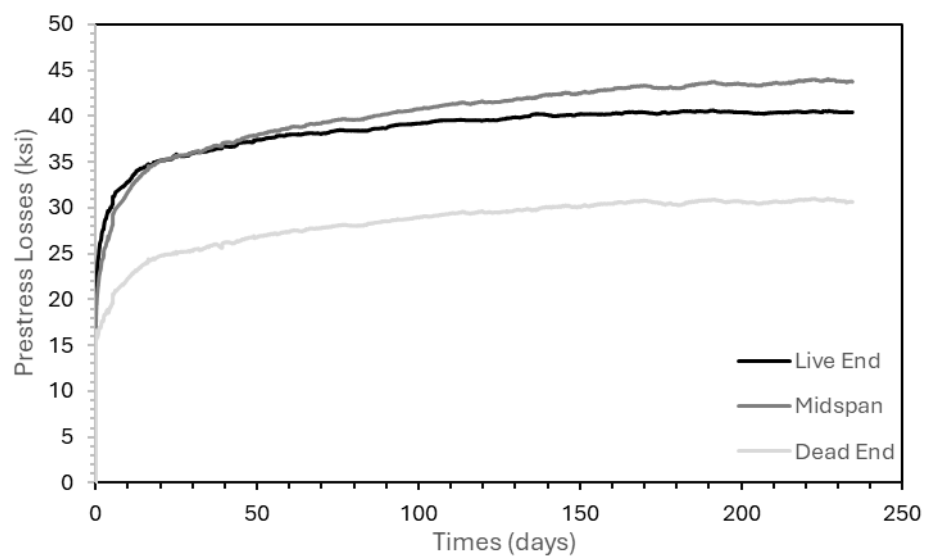


Figure 43. Measured prestress losses over time for specimen H-UHPC-SCC 1

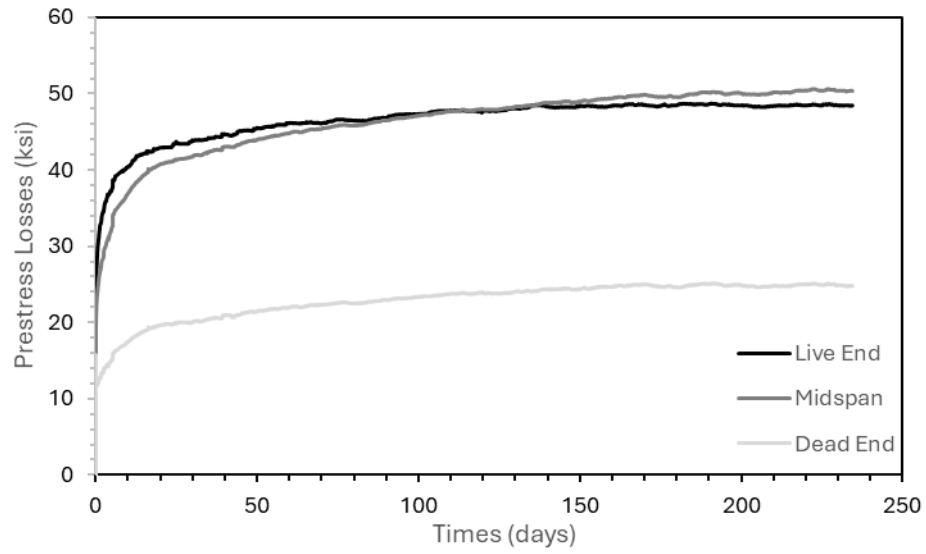


Figure 44. Measured prestress losses over time for specimen H-UHPC-SCC 2

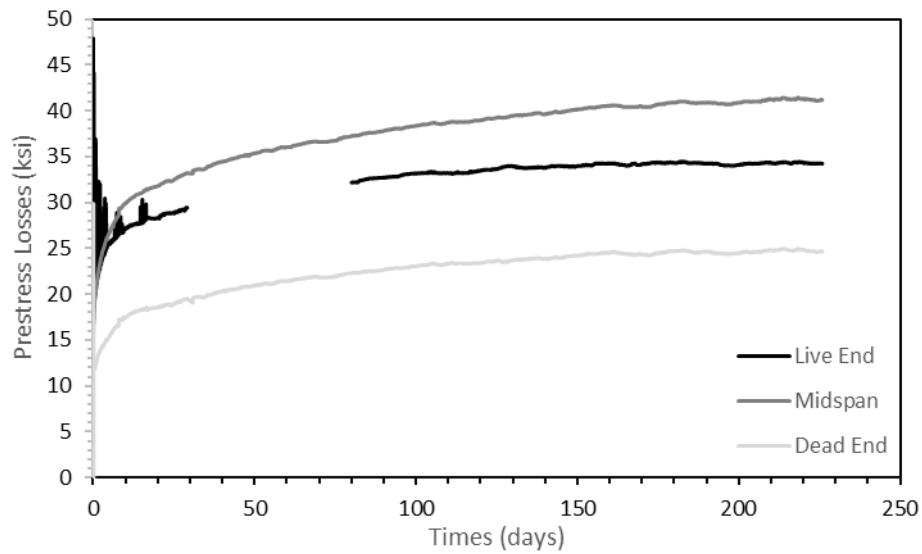


Figure 45. Measured prestress losses over time for specimen H-UHPC-SCC 3

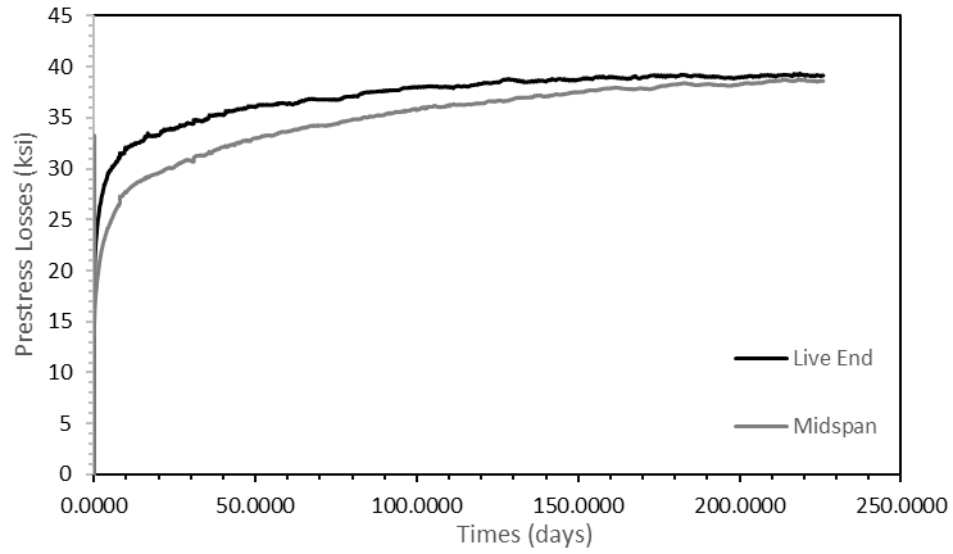


Figure 46. Measured prestress losses over time for specimen H-UHPC-SCC 4

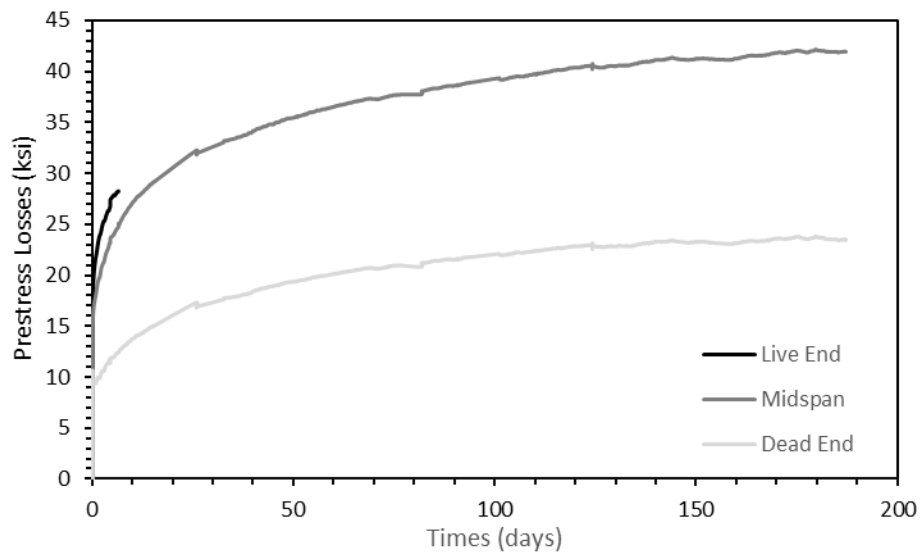


Figure 47. Measured prestress losses over time for specimen H-UHPC-SCC 5

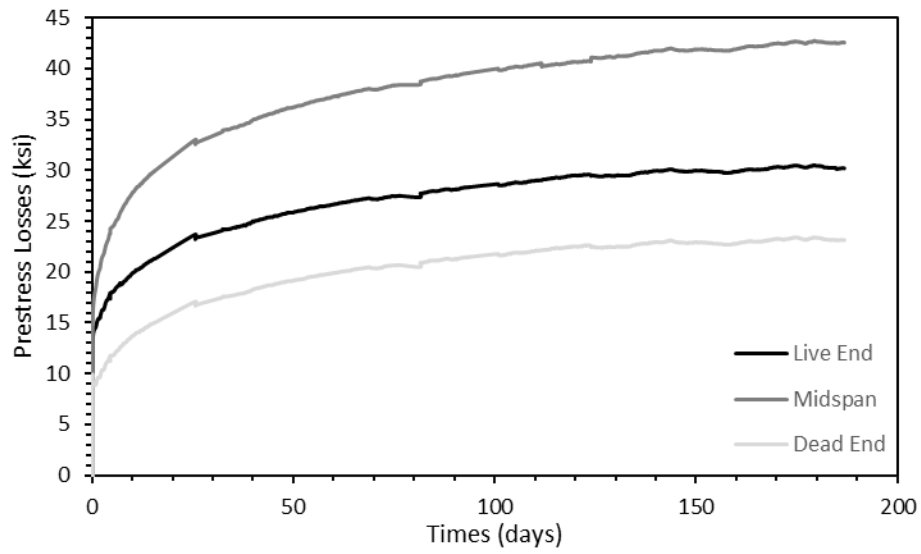


Figure 48. Measured prestress losses over time for SCC specimen

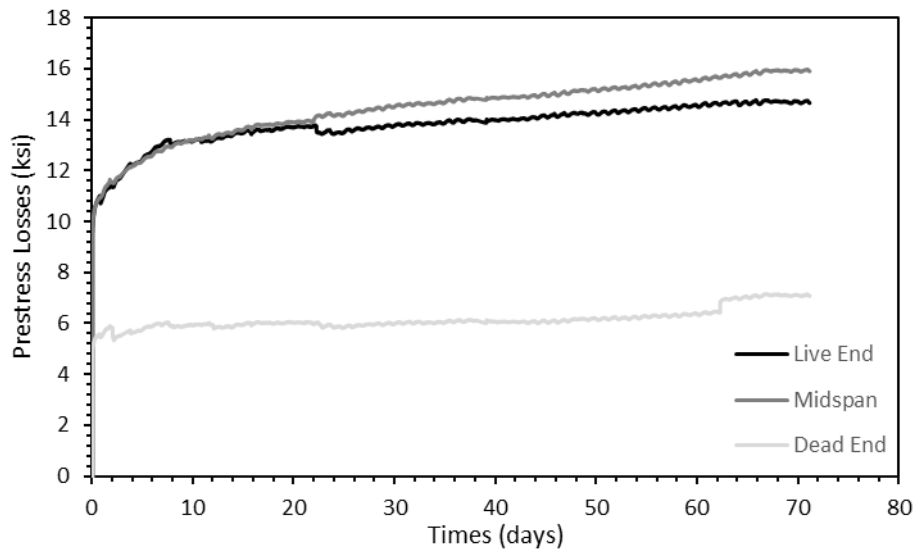


Figure 49. Measured prestress losses over time for specimen UHPC-CS 1

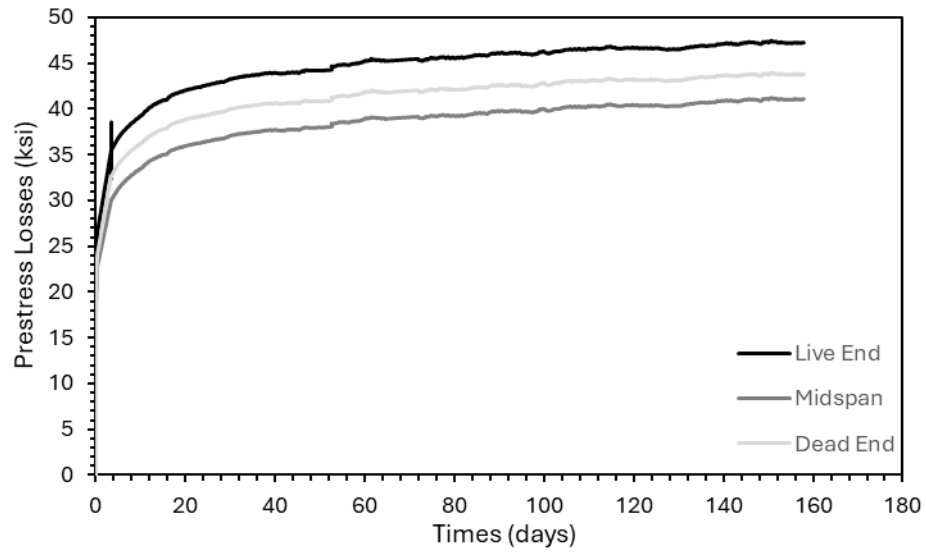


Figure 50. Measured prestress losses over time for specimen UHPC 1

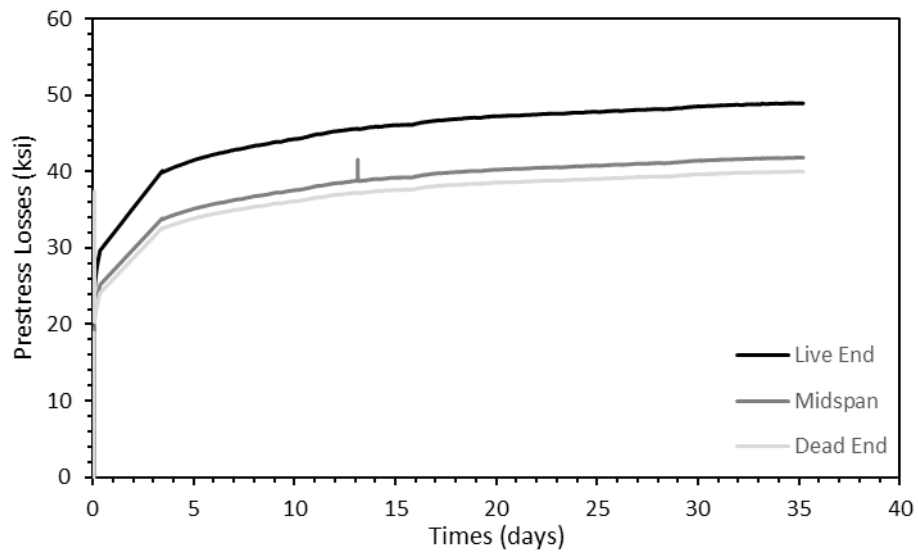


Figure 51. Measured prestress losses over time for specimen UHPC 2

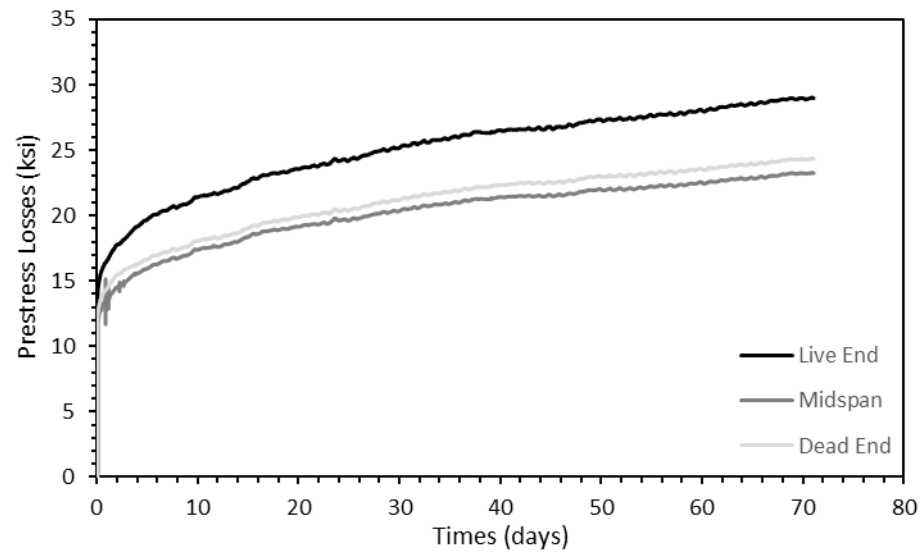


Figure 52. Measured prestress losses over time for specimen UHPC 3