Interface Shear Performance of Full-Scale Composite UHPC Box Beams

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Abstract

A new ultra-high-performance concrete (UHPC) composite beam section was developed for use on short-span bridges in Pennsylvania. Due to the shallow nature of the section, interface shear strength plays a significant role in the design of the system. In order to enhance the horizontal shear capacity between the UHPC precast beam and cast-in-place (CIP) conventional concrete deck, either increase the stirrups at interface or an intentionally roughened top flange surface of the UHPC beam are considered. Due to the rheology of UHPC, conventional scoring techniques are not effective in creating adequate roughness. Therefore, keyed surface on the top flange which serves as the intentionally roughed surface is proposed in this study. Two designs for the connections between the concrete deck and the UHPC beam are presented and compared. It was found that the design with keyed surface reduce the usage of interface stirrup by 92%, therefore is preferred and selected for further investigation. Two composite UHPC box beams will be experimentally investigated in the future study. Different factors affecting the horizontal shear capacity of the composite UHPC beam will be discussed, namely, the geometry of keyed surface, and effective interface reinforcement details.

Keywords: UHPC, composite section, box beam, interface shear, keyed surface

1. Introduction

Ultra-high-performance concrete (UHPC) is a new-generation self-consolidating fiber-reinforced Portland cement concrete with outstanding mechanical properties and durability. Figure 1 shows the stress-strain relationships of Cor-Tuf UHPC. Cor-Tuf is the name that was given to a family of UHPCs developed at the U.S. Army Engineer Research and Development Center (ERDC) (Vicksburg, Mississippi). As shown, the compressive strength of the Cor-Tuf UHPC is 25.0 ksi (172.37 MPa) and the ultimate tensile strength is 1.2 ksi (8.27 MPa). Compared to the conventional concrete, UHPC has a significantly greater compressive strength and ultimate tensile strength.

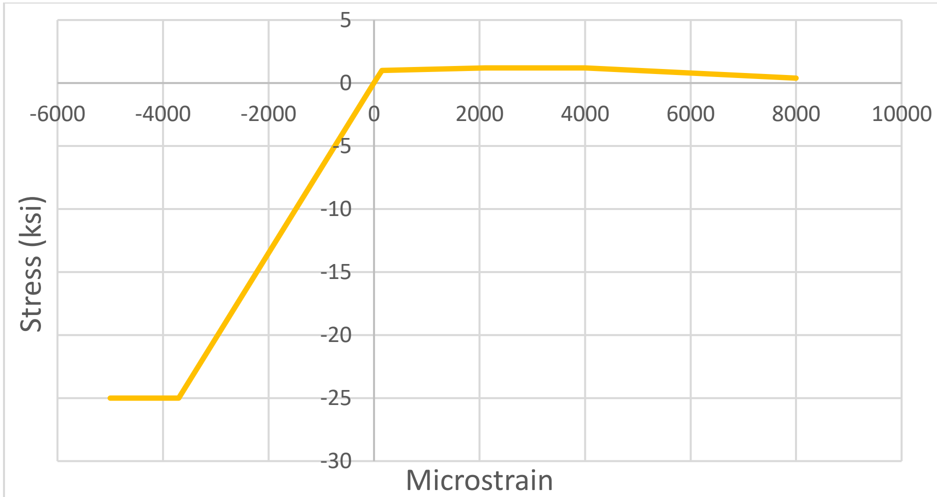

Figure 1. Stress-stress relationships of UHPC provided by Cor-Tuf.

Over half of the 599,766 bridges in the United States are approaching the end of their design life and nearly a quarter need significant retrofit or replacement to eliminate deficiencies (Ghosh and Padgett). The bridges made by UHPC with smaller sections and better durability, which facilitates the replacement progress and reduces the cost of maintenance during the life cycle, can be an excellent alternative. To facilitate the use of UHPC in the bridge replacement applications, this research develops a new UHPC composite beam for short span bridges. As short span bridges are the most common bridges in service. For example, according to HAZUS data, approximately 75% bridges in PA have the span length less than 32 feet.

The UHPC composite beam is the production of the UHPC precast box beam and cast-in-place (CIP) conventional concrete deck. The UHPC precast box beam is adapted from the standard box beam specified in (*Standard Drawings for Bridge Design, BD-600M Series (Pub. 218 M)*), but is detailed to be shallower than current specifications allow. The shallow section could provide more space underneath and therefore could facilitate bridge replacements where additional truck heights or hydraulic openings are needed due to increased regional hydraulic demands due to climate change. In addition, the shallow box section type allows the beam to be readily installed with smaller cranes and equipment commonly available in county bridge jurisdictions.

Due to the shallow nature of the section, interface shear strength plays a significant role in the design of the composite beam. Either increase the steel stirrups at the interface or create an intentionally roughened top flange surface of the UHPC beam can enhance the interface shear capacity between the UHPC precast box beam and cast-in-place (CIP) conventional concrete deck. Due to the rheology of UHPC, conventional scoring techniques are not effective in creating adequate roughness. Therefore, a keyed surface on the top flange of the UHPC box beam which provides adequate roughness is proposed in this study. Two designs of the UHPC composite beam are presented in the paper: Design A examines a beam without an intentionally roughened interface, while Design B includes a keyed surface on the top flange of the UHPC beam. Design B with a keyed interface, provides savings in reinforcement materials and improved constructability with the added cost involved in fabrication of the keys.

2. Overview of the Short Span Bridge

Figure 2 shows the cross section of a short span bridge. This bridge is simply supported, has a span length of 35 feet (10.67 m), and is comprised of two concrete barriers, a cast-in-place (CIP) conventional concrete deck and five UHPC precast box beams spaced at 9.57 feet (2.92 m). The total width of the bridge is 44.38 ft (13.53 m), which is a two-lane bridge with a 12 ft (3.66 m) right shoulder and 5 ft (1.52 m) left shoulder. The design is based on (*AASHTO LRFD Bridge Design Specifications*) (AASHTO), (*Pennsylvania Design Manual, Part 4 (DM-4)*) (PA DM-4) and (*AASHTO Guide Specification for Structural Design with Ultra-High Performance Concrete*) (AASHTO Guide). The 28-day compressive strength of deck concrete is 6 ksi (41.37 MPa). The properties of Cor-Tuf UHPC used in design is shown in Figure 1. The prestressing strand is 0.6 in (15.24 mm) diameter with 270 ksi (1,861.58 MPa) tensile strength. Two live load combinations were considered in the design, including Strength I combination and Strength II combination specified in AASHTO and PA DM-4. The section of the UHPC beam is shown in Figure 3. As shown, the precast beams are 15 in (381 mm) deep, 48 in (1219.2 mm) wide, and have a 2 in (50.8 mm) thick top flange, 3-1/8 in (79.38 mm) thick bottom flange, and 5 in (127 mm) thick web. For comparison, Figure 4 shows a conventional concrete box beam section, which is designed under the consideration of the same beam spacing and the number of prestressing strands as the UHPC box beam. The 28-day compressive strength of the concrete for this box beam is 10 ksi. The results show that the cross-sectional area of the UHPC beam is reduced by 29.8% compared to the conventional concrete box beam.

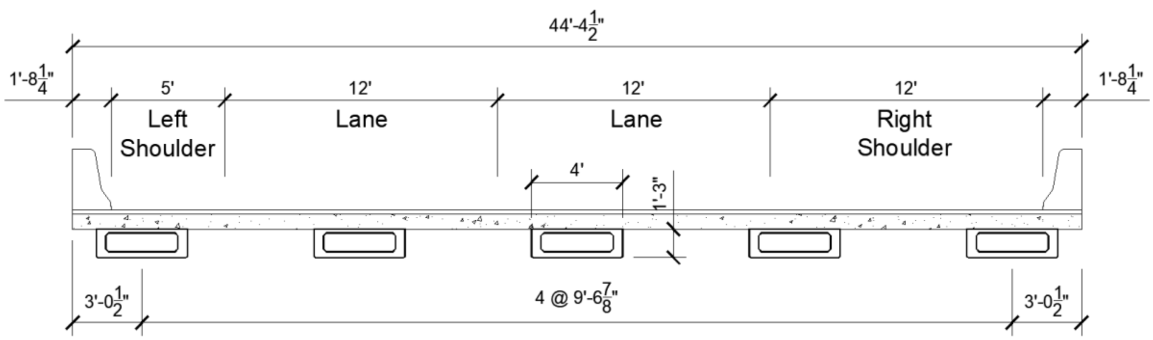

Figure 2. Cross-section of short span bridge.

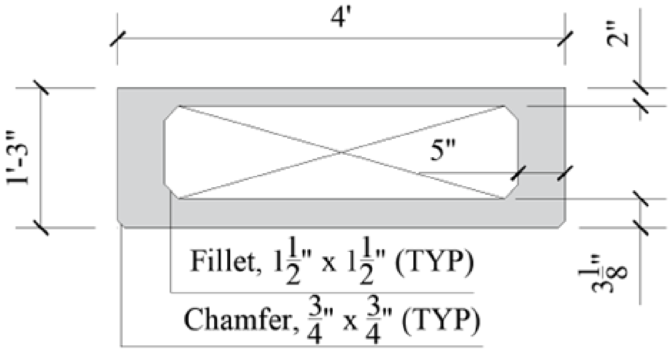

Figure 3. Cross-section of UHPC box beam.

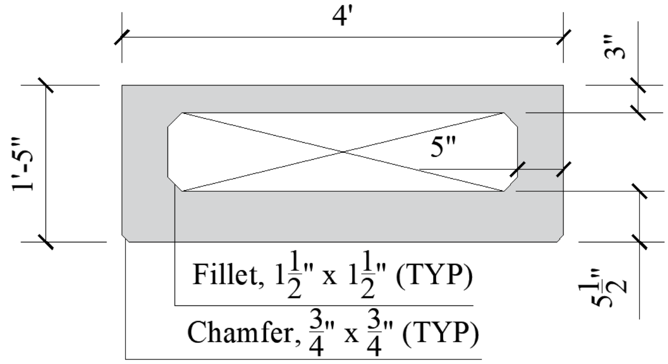

Figure 4. Cross-section of conventional concrete box beam.

3. Interface Shear Design

The design provisions are given in Article 5.7.4.3 of AASHTO, and the nominal shear capacity of the interface plane is as follows:

$$\boldsymbol{V.ni = c \cdot Acv + \mu \cdot (Avf \cdot fy + Pc)} \quad \text{(Equation 1)}$$

where:
c = cohesion factor specified in Article 5.7.4.4 of AASHTO (ksi)
μ = friction factor specified in Article 5.7.4.4 of AASHTO
Acv = area of concrete considered to be engaged in shear transfer (in^2)
Avf = area of interface shear reinforcement crossing the shear plane within the area Acv (in^2)
fy = yield stress of reinforcement but design value not to exceed 60.0 (ksi)
Pc = permanent net compressive force normal to the shear plane; if force is tensile, Pc = 0.0 (kip)

As noted in Equation (1), the nominal interface shear capacity is a function of the cohesion factor and friction factor. The following cohesion and friction factors are recommended for the various interface conditions:

Table 1. Cohesion and friction factors

Interface condition	Specification	Cohesion Factor	Friction Factor
Intentionally Roughened	AASHTO	0.24 ksi	1.0
	AASHTO Guide	0.075 ksi	1.0
	(Tadros et al.)	0.24 ksi	1.0
Not Intentionally Roughened	AASHTO	0.075 ksi	0.6
	AASHTO Guide	0.075 ksi	0.6
	(Tadros et al.)	0.025 ksi	0.7

3.1. Design A

Design A was conducted with an interface surface which is not intentionally roughened. Based on Article 5.7.4.4 of AASHTO and Article 1.7.4.4 of AASHTO Guide, not intentionally roughened concrete surface shall use a cohesion factor of 0.075 ksi (0.52 MPa) and a friction factor of 0.6. The yield strength of the stirrups used in the design is 60 ksi (413.69 MPa). The required stirrups for Design A are shown in Figure 5 and Figure 6. As shown, large amounts of stirrups are needed to provide adequate interface shear capacity. A total of 196 lbs of #5 interface shear reinforcement is needed per beam.

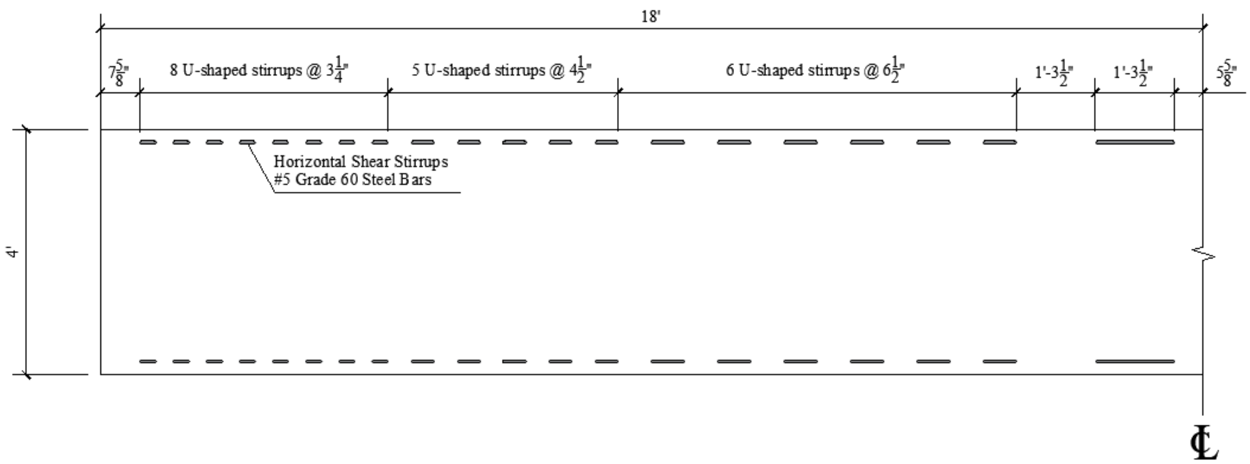

Figure 5. Plan view of interface stirrup details of Design A.

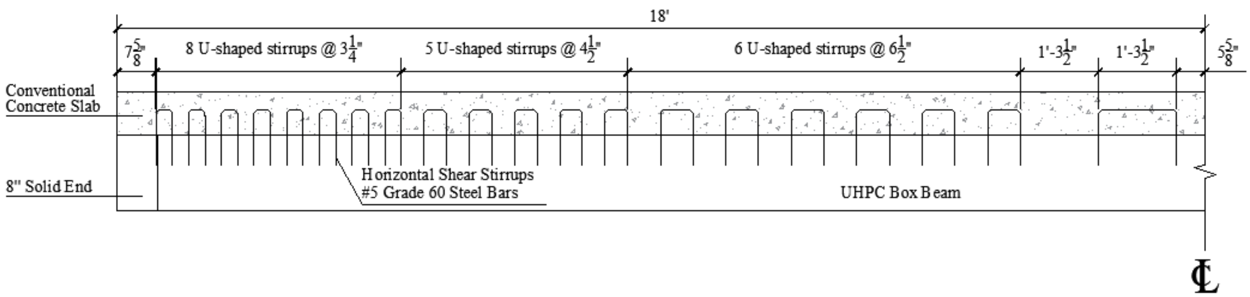

Figure 6. Interface stirrup details of Design A.

3.2. Design B

To reduce the required amount of interface reinforcement, and to reduce tripping hazards on the erected beams, Design B utilizes a roughened interface. According to Article 5.7.4.4 of AASHTO and (Tadros et al.), the roughened surface has a cohesion factor of 0.24 ksi (1.66 MPa) and a friction factor of 1.0. Due to the rheology and fiber content of UCHP, roughening the surface with rakes or brooms is not viable. (Tadros et al.) proposed the use of a form liner to create a keyed surface. Keyed surface properties have been recommended by (Tadros et al.) and (*EN 1992-1-1: Eurocode 2: Design of Concrete Structures - Part 1-1 : General Rules and Rules for Buildings*) (Eurocode 2). (Tadros et al.) requires the maximum length of the keys to be less than 6 in. (152.4 mm) or 10 times the depth of the key, while the Eurocode 2 only requires that the length be less than 10 times the depth of the key. According to the requirements of (Tadros et al.) and Eurocode 2, a keyed surface is detailed. The geometry of the keyed surface including the plan and elevation views are shown in Figure 7 and Figure 8, respectively. The roughened surface is assumed to be the width of the key, which is 35 in. (889 mm). The 6.5 in. regions on the side of the keys are considered as not intentionally roughened and provide a lower cohesion factor. The friction factor for the entire top surface is taken as 1.0. The required stirrups for Design B are shown in Figure 9.

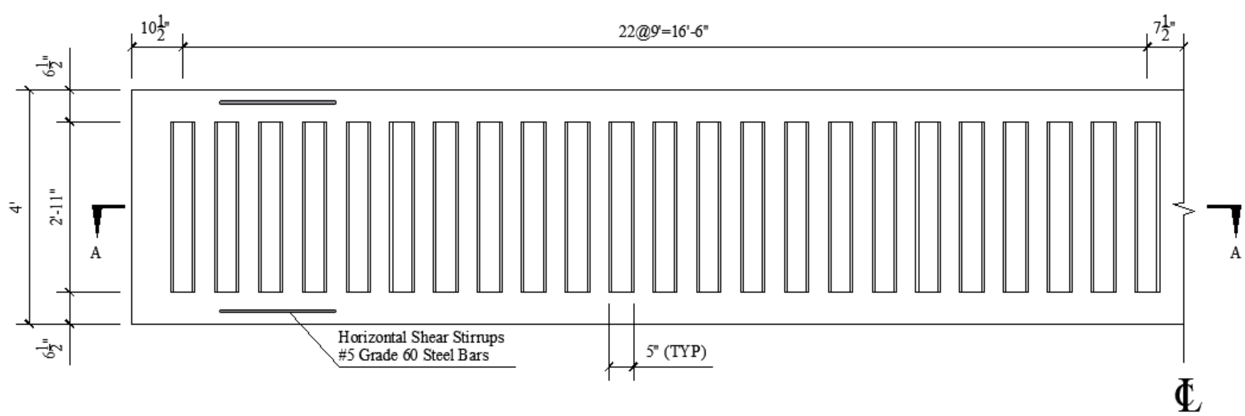

Figure 7. Plan view of Design B UHPC box beam.

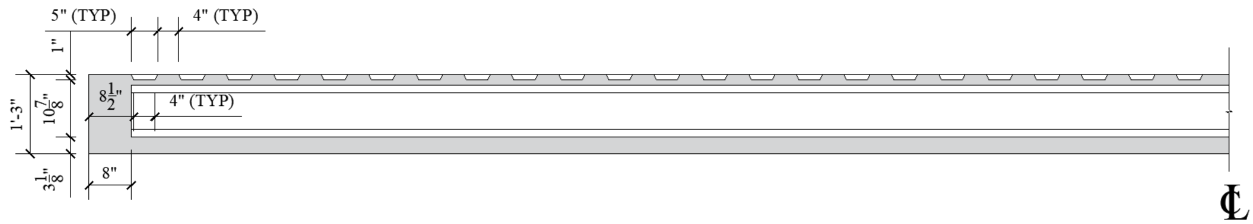

Figure 8. Elevation view of Design B UHPC box beam (A-A section).

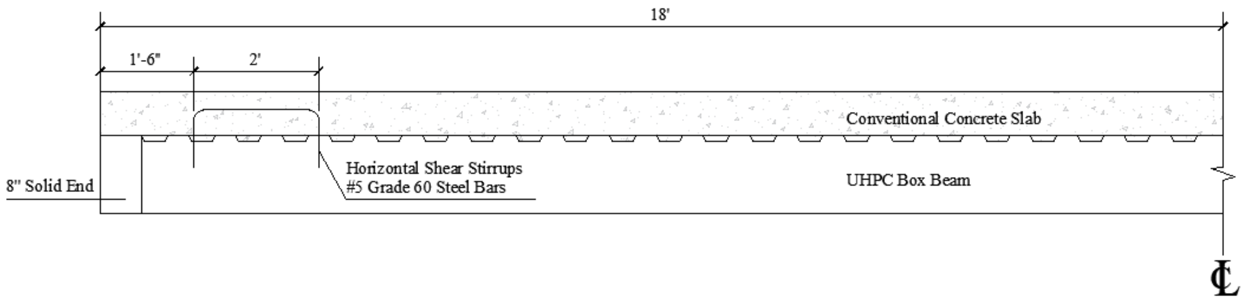

Figure 9. Interface stirrup details of Design B.

Comparison of Design A and Design B results in a decrease in the number of stirrups lowering the total weight of steel from 196 lbs to 16 lbs. With the keyed surface, the use of stirrups could be reduced by 92%, which can reduce material costs and labor needed to fabricate the stirrups and install them. This is offset by the additional cost of the form liner needed to create the keyed region. The keyed impressions also result in a reduction in the amount of UHPC materials required which further reduces the cost. Therefore, the keyed surface UHPC box beam is preferred and selected for further investigation.

4. Future Laboratory Test

Two full-scale composite beam test specimens are designed per Design B. As mentioned above, the limitation on the length of the keys is different per (Tadros et al.) and Eurocode 2. Besides, according to AASHTO, for beams or girders, the longitudinal center-to-center spacing of nonwelded interface shear connectors shall not exceed 48.0 in (1219.2 mm) or the depth of the member. To better understand the effects of the geometry of the key on the interface shear capacity and to study the effect of stirrup spacing on the interface shear capacity, two full-scale composite beams with various key geometries and interface reinforcement spacings will be tested to study the performance under service load and the capacity of interface shear.

5. Conclusions

As discussed, the use of UHPC provides the opportunity to design lighter and more efficient beam sections for short span bridge replacements. This design concept can allow for increases in hydraulic bridge openings on replacement projects and can be readily installed due to their low weight. The hurdle for the design is the high interface shear forces that must be transferred. This summary paper provides two potential beam designs. The sections will be examined experimentally with results forthcoming.

6. References

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