An Analytical Study of the Structural Performance of Hybrid Deck Bulb Tee (HDBT) Elements for Superstructure Replacement

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Abstract

Approximately 7.5% of bridges in the United States are deemed structurally deficient, with a current backlog of bridge repair costs standing at $125 billion. In the years to come, there is a need for bridge replacements, as well as improved materials and building methods to guarantee the durability of such structures. To this end, a new hybrid beam element known as the Hybrid Deck Bulb Tee (HDBT) has been proposed. This HDBT uses a staged fabrication process to tackle existing limitations of pre-stressed beams, such as unpredictable camber and tension in the top flange. The bottom flange is cast with Ultra-High-Performance Concrete (UHPC) and pre-stressed before the web and top flange are cast with High-Performance Concrete (HPC). This results in the main component of tension existing in the bottom flange for standard beams. Pre-compression applied to the bottom flange of the HDBT removes this tension and also eradicates the propensity for cracks at the end of the beam and decking, due to the load being applied in the HDBT's manufacturing process. The HDBT's manufacturing process enables more accurate predictions of camber and also allows for a significant reduction in the size and depth of the beams. This paper details an analytical study to evaluate the structural performance of the proposed HDBT elements.

Keywords: UHPC-HPC composite elements, Deck Bulb Tee (DBT), precast beam, superstructure replacement, simple-span bridges.

Introduction

Approximately 7.5% of bridges in the United States are deemed structurally deficient, with a current backlog of bridge repair costs standing at $125 billion (ASCE, 2021). In the years to come, there is a need for bridge replacements, as well as improved materials and building methods to guarantee the durability of such structures. Prestressed concrete beams make up over 40% of bridges with a span length over 30 ft (10 m) (USDOT, 2023). Despite this prevalence, over the last five decades there have been few advancements in the state of the for the design and construction

of prestressed concrete structures. For example, the Decked Bulb Tee (DBT) girder, has been used since the 1980s decade with minimal innovation in materials and production (Grace et al, 2015).

There are four drawbacks with the fabrication processes of traditional prestressed concrete girder superstructures (Graybeal & Tanesi, 2007; PCI, 2014; Torres et al, 2020): (1) the durability of existing prestressed concrete structures when exposed to corrosive environments is well below desired levels as evident by the severe level of corrosion observed on in-service bridges, (2) the standard fabrication methods for prestressed concrete beams generate tensile stress at the endzone or bursting forces as an unintentional subsequent effect, (3) the current design method is restricted by the maximum allowable tensile stress at the extreme fiber of the top flange near both ends, (4) variations in the camber of prestressed concrete beams can demand considerable corrective measures in the field.

Recent advances in cementitious materials have provided opportunities for advance both beam design and fabrication procedures, while resolving the current constraints of prestressed concrete bridge beams. The development of Ultra High-Performance Concrete (UHPC) has been one of the most striking improvements in cementitious materials technology in recent decades. UHPC offers increased tensile strength, compressive strength, permeability resistance, and durability (Graybeal, 2011, 2014) compared to conventional or High-Performance Concrete (HPC). Investigators are currently researching the performance bridge girders fully composed of UHPC (Binard, 2017; El-Helou & Graybeal, 2019). Nevertheless, full UHPC girders produced with standard fabrication steps do not solve the previously mentioned issues of prestressed beams, such as tension in the top flange and unpredictable camber. This last issue is noted by Sim et. al (2020) when discussing the design of precast, prestressed UHPC elements. In addition, the research on prestressed UHPC girders is mainly focused on bridges with long-span over 250 ft (76.2 m) (El-Helou & Graybeal, 2019; Sim et al, 2020). While UHPC girders are a promising option for long-span applications, over 95% of girder bridges in the US have spans under 150 ft (45.7 m) (USDOT, 2022). In this span range, there are over 40,000 girder bridges with a superstructure considered in fair condition (rating of 5.0) or structurally deficient (rating 4.0 or below), which makes them promising candidates for a superstructure replacement.

Another key consideration is that superstructures using prestressed HPC girders cannot contend with steel girder superstructures in terms of dead load and vertical clearance. Thus, there is a clear challenge replacing steel girder superstructures with prestressed concrete girders. To address this limitation, along with the aforementioned drawbacks in the fabrication of traditional prestressed beams, the Hybrid Deck Bulb Tee (HDBT) is presented. The HDBT, a new hybrid beam element, is fabricated in multiple stages in which the bottom flange is cast with UHPC and prestressed, after that the web and top flange are cast with HPC. The HDBT benefits from an novel design including: (1) the staged fabrication allows for control of camber as well as the differential camber between units, which can eliminate the need for corrective measures in the field, (2) prestressing is only induced in the bottom flange, which avoids the development of tension in the top flange and prevents cracking in the end zone, and (3) using UHPC in critical regions and HPC for the web and flange to reduce costs.

This paper will summarize the fabrication procedure along with an analytical study in CSiBridge (CSI, 2019) to evaluate the structural performance of the proposed HDBT elements.

HDBT Fabrication

The HDBT is produced in a staged process. This includes (1) assemble the UHPC bottom flange form, (2) place the steel reinforcement and the strands, which should be placed in such a way that the resultant force coincides with the bottom flange cross-section centroid, (3) apply tension to the strands, (4) cast and cure UHPC, (5) prepare top surface of UHPC to provide bond with the HPC, (6) release strands in the bottom flange when the specified compressive strength is reached, inducing compression to the UHPC bottom flange, (7) given that no camber is expected, shore the bottom flange to set to the required profile, (8) assemble the web and top flange form and provide crack control reinforcement and deck reinforcement, (9) cast and cure HPC, and (10) remove forms when HPC reached specified strength. A schematic of the final element is shown below in Figure 1.
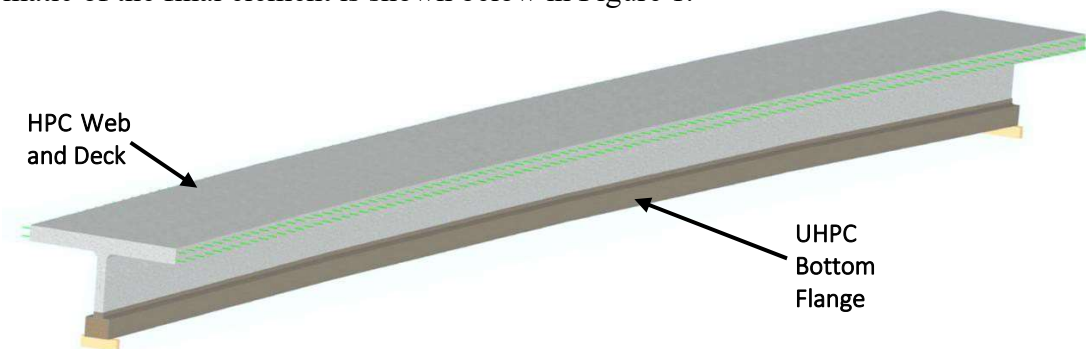

Figure 1. Schematic showing final view of HDBT element after form removal.

HDBT Design and Analysis

The following section details a sample design for a 120 ft (36.6 m) single-span bridge. The cross section is composed of four HDBT beams spaced 8 ft (2.44 m). The external beam overhang is 3.5 (1.07m). Therefore, the interior girder width is 8 ft (2.44 m) and the interior girder width is 7.5 ft in (2.29 m). The bridge is designed for AASHTO's HL-93 live load (2020). A 3-in (75 mm) wearing surface and a 0.50 kips/ft (7.3 kN/m) barrier are included as dead load. Regarding the barrier, 50% of the load is applied to the external beam and the remainder to the next internal beam. The deck thickness is 8 in (203 mm), and a 0.5 in (13 mm) asphalt wearing surface is included.

The design process of the HDBT was iterative using CSiBridge (CSI, 2019). The analysis included all phases of the stage fabrication to capture stress accumulation and strain compatibility between stages. The UHPC bottom flange was modeled with frame elements and included the prestressing strand group that was modeled with a single tendon element with an equivalent area located at the center of gravity of the strand pattern. The HPC web and top flange were modeled with shell elements. The support conditions were defined as a pin-roller condition. The wearing surface and parapets are defined as area loads and line loads, respectively. A view of the overall model is shown in Figure 2. The compressive strength of the UHPC was defined as is 14 ksi (100 MPa) at strand release with a 28-day strength of 22 ksi (150 MPa). The UHPC effective cracking stress is assumed as 1 ksi (6.7 MPa). The specified HPC compressive strength is 10 ksi (70 MPa).

Both concrete materials are normal weight concrete. The strands are grade 270 ksi (1850 MPa). The prestressing stress 202.5 ksi (1388 MPa). The relative humidity for losses calculation is 70%.
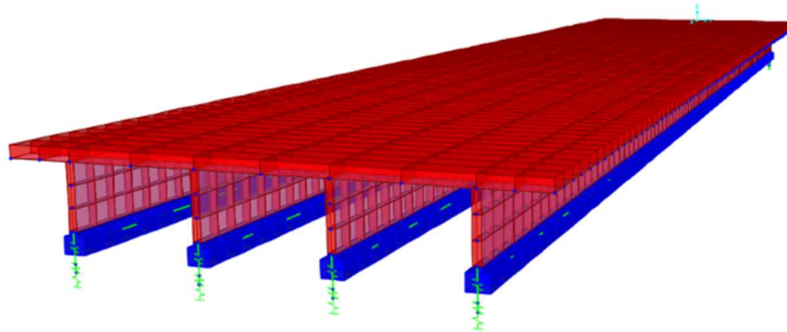

Figure 2. 3-D view of model from analysis showing full 120-ft (36.6-m) single span four-beam bridge with HDBT elements.

The final design is shown below in Figure 3. The web thickness is 6 in (152 mm). The bottom flange is 16 in (406 mm) width and 12 in (305 mm) depth. The total height of the section is 72 in (1.83 m). Strength checks were performed using the HPC design properties, including moment (AASHTO LRFD 5.6.3.2), shear (AASHTO LRFD 5.7.3.3) and interface horizontal shear (AASHTO LRFD 5.7.3.3) capacities.
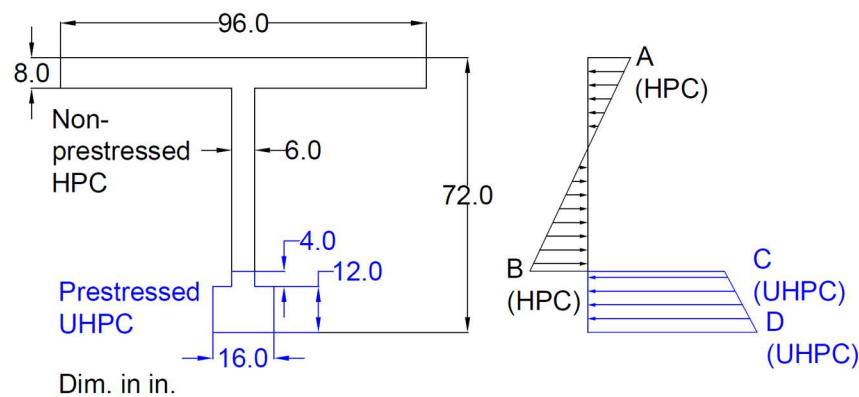

Figure 3. Interior HDBT beam dimensions shown in inches and corresponding flexural stress distribution for service loads.

The elastic modulus of HPC and UHPC was calculated with equation AASHTO LRFD C5.4.2.4-1 (El-Helou et al, 2022). Regarding the distribution factor calculation, the girders are considered sufficiently connected to act as a unit in order to apply AASHTO LRFD 4.6.2.2.2. Service limit states were checked following AASHTO LRFD for the HPC material. The estimate of time-dependent losses in UHPC was calculated according to Mohebbi and Graybeal (2022). AASHTO LRFD's compression stress limits for conventional concrete were used for UHPC (El-Helou & Graybeal, 2022). The tensile stress limit is taken as a fraction of the stress limit with a reduction factor of 0.85 (El-Helou & Graybeal, 2022).

The tension stress in the HPC-UHPC interface is critical to the HDBT design (labeled as point B in Figure 3). The resultant tension stress in the HPC web was compared with the design flexural cracking stress (AASHTO LRFD 5.9.5.4.4c) which is the modulus of rupture (AASHTO LRFD 5.4.2.6) reduced with a 0.85 reduction factor. The HDBT design is governed by the tensile stress value of the non-prestressed HPC web at the interface with the UHPC bottom flange at service limit. This can be addressed with distributed reinforcement according to AASTHO LRFD 5.6.7, as mentioned in the construction process. With this context, bridge owners can specify an admissible level of cracking as a design requirement.

Results and Discussion

The PCI Bridge Design Manual (PCI, 2014) was chosen as reference given the availability of multiple preliminary designs, based on AASHTO LRFD Specification 2010 (AASHTO, 2010). Despite the differences between 2010 and 2020 AASHTO Specifications, the PCI Manual is a good reference point. The main differences between these codes are: (1) the compression stress limit for temporary stress losses was increased from a ratio from 0.60 to 0.65 of the specified compressive strength, (2) a limit of 0.60 ksi (4.13 MPa) was included for the tensile stress at service limit after losses, and (3) the introduction of the design flexural cracking stress. Other changes that do not affect this example, therefore could affect other designs are: (4) introduction of the correction factor for concrete density, (5) the elimination of extreme dimensions for thickness of webs and flanges thickness of concrete precast beams, (6) the calculation of the modulus of rupture was simplified to a single equation, and (7) the variability of the stress block factor for design compressive strengths of concrete exceeding 10 ksi (700 MPa).

Figure 4 shows the comparison the total weight of the beam and deck for the different designs, between PCI Manual's preliminary designs (grey bars) and HDBT (orange bars), for both exterior (labeled as Ext.) and interior (labeled as Int.) beams. Regards to dead load, the HDBT is the most efficient design, with a 12 and 16% reduction compared to the next lightest design for interior and exterior beam, respectively. This dead weight can be reduced using lightweight HPC.
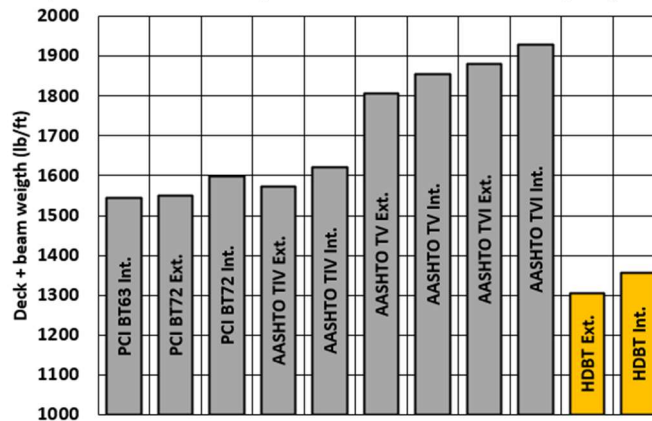

Figure 4. Comparison of beam weights for 120-ft (36.6-m) single span PCI Manual preliminary designs and HDBT preliminary designs for exterior (Ext.) and interior (Int.) beams. Note that barrier, haunch, and wearing weights are not included. PCI BT = PCI Bulb Tee standard section, AASHTO = AASHTO standard section.

Conclusions

This paper introduced a new prestressed concrete alternative for short-and mid-span superstructure replacement projects that can compete with steel girders in terms of weight and section depth. In addition, the fabrication process addresses several challenges associated with current prestressed concrete girders. The HDBT uses UHPC in critical regions and HPC for the web and flange to reduce costs, while providing a design with predictable camber and no tension in the top flange. The analytical study conducted for the HDBT showed the proposed design and construction is structurally viable and was successful in reducing dead load up to 16% compared to the preliminary designs from the PCI Bridge Design Manual. This research provides evidence that the HDBT is a viable approach to bridge repair and replacement and could be used to address the current structural deficiencies facing the US bridge network.

Acknowledgements

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