Ultra-High-Performance Concrete Optimization of Double-Tee Bridge Beams

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Ultra-high-performance concrete (UHPC) was first introduced as reactive powder concrete in the early 1990s by employees of the French contractor Bouygues. Since then, France, Japan, and several other countries have made significant progress in using this material for bridge construction and other applications. The first roadway bridge with UHPC beams was built in France in 2001.[1] It was made of five 2-ft-11-in.-deep double-tee (DT) beams (**Fig. 1a**) and had two equal spans of 72 ft 2 in. each. The beam section had two stems with bottom bulbs to allow placement of prestressing strands and was referred to as a "π-shaped beam."

In the United States, several state departments of transportation are exploring applications of UHPC for their bridge projects; the use of UHPC for some projects has been supported by the Federal Highway Administration (FHWA) and research performed by local universities. Most notably, Iowa has built several bridges with UHPC components. In 2008, Iowa built a bridge in Buchanan County with a π-shaped beam similar to the French section (**Fig. 1b**). The bottom bulb of the Iowa bridge was influenced by Massachusetts Institute of Technology[2] and FHWA[3] research (for more information on this bridge, see the Project article in the Winter 2010 issue of *ASPIRE*®). Several companies currently market prepackaged UHPC in the United States. The material has mostly been used in joints between precast concrete members.

To advance UHPC applications in the United States, the Precast/Prestressed Concrete Institute (PCI) has awarded an implementation project led by e.construct, with participation from Wiss, Janney, Elstner Associates; the University of Nebraska-Lincoln; North Carolina State University; and Ohio State University. This ongoing project focuses on assisting six participating precasters in developing their own UHPC mixtures at a lower cost than commercial prepackaged materials, thus enabling development of precast, prestressed concrete bridge and building members at an initial cost competitive with the cost for conventional concrete (CC) members. The research project is scheduled to be completed in 2021. It will include materials and structural design guides with fully worked design examples. So far, the project team has successfully helped all six precasters develop acceptable UHPC mixtures for use in their current production facilities. Also, preliminary conservative design guidelines have been developed based on published national and international research. After full-scale testing is performed in 2020, these guidelines will be refined to produce additional optimization.

Even when using the proposed preliminary design guidelines for the design of pretensioned bridge girders, significant savings in concrete quantities and near elimination of reinforcing bars can be realized.

Definition of UHPC

There is currently no universally accepted definition of UHPC. Design compressive strengths of UHPC typically range from 17 ksi to 22 ksi. The PCI project defines a minimum compressive strength at transfer of 10 ksi and at service of 18 ksi. While these compressive strengths are higher than the compressive strength of typical concrete used for pretensioned girders, the material properties of UHPC that provide the most significant benefit for structural design are the tensile strength and tensile ductility. The steel fibers in UHPC result in these tensile properties being much higher in UHPC than in CC. The PCI project recommends that results from tests of

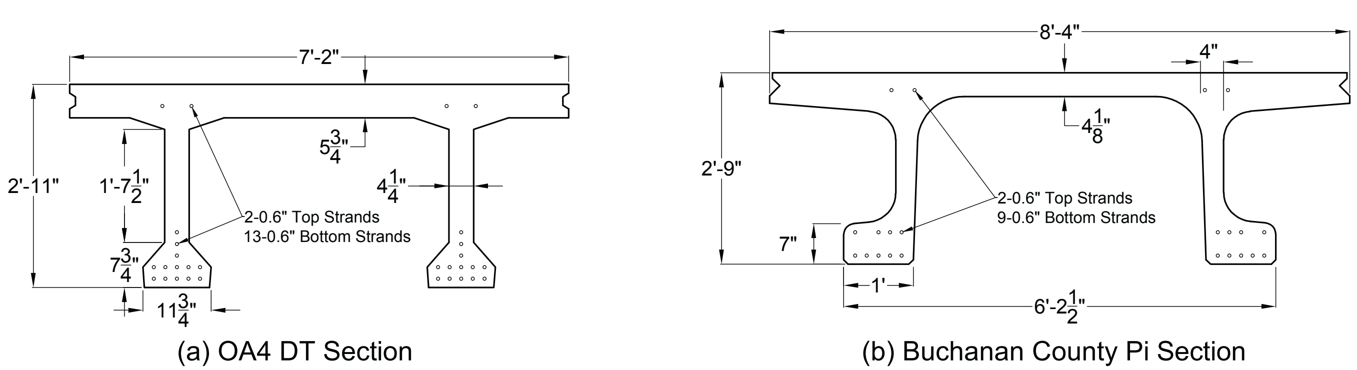


Figure 1. Cross sections for (a) π-shaped beam in France[1] and (b) π section in Buchanan County, Iowa.[2,3] Figure: e.construct.

UHPC performed according to ASTM C1609 *Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete*[4] provide a tensile strength at first cracking of at least 1.5 ksi and peak tensile strength of at least 2 ksi with significant deflection (ductility) beyond cracking (**Fig. 2**). This high tensile strength allows for much higher shear resistance and the possibility of total elimination of stirrups. The flexural (tensile) strength of fiber-reinforced concrete prisms determined according to ASTM C1609 can be correlated to shear (diagonal tensile) strength. The fibers essentially act as randomly oriented tensile elements crossing the potential diagonal cracks, and this enhances the diagonal tensile capacity.

A typical mixture for 1 yd³ of UHPC consists of 1200 lb of cement, 150 lb of silica fume, 570 lb of slag (or another supplementary cementitious material), and 1640 lb of fine sand, as well as water-reducing and workability admixtures. The water-to-binder ratio is about 0.18. Fibers are added at 2% by volume, or about 265 lb/yd³. The estimated material cost of this mixture would be about $650 to $800/yd³, which compares favorably to the $2000 to $3000/yd³ cost of commercial prepackaged mixtures.

UHPC Criteria and Structural Design Guidelines

In the authors' professional opinion, the published literature and other countries' codes provide sufficient knowledge to conservatively perform UHPC beam design until refinements are developed and guide specifications are published. For a prestressed UHPC beam element, flexural design is quite similar to design with CC. The contribution of the steel fibers in UHPC to a beam's flexural strength

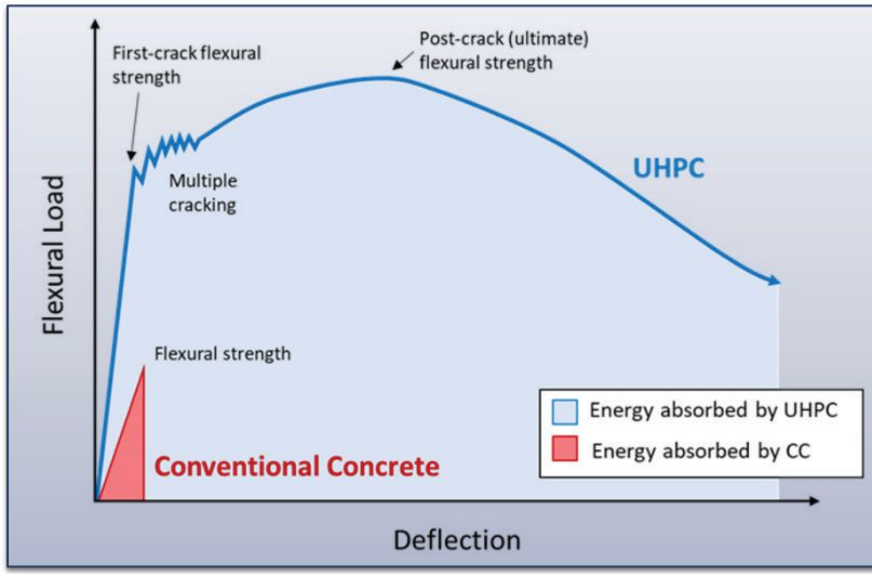


Figure 2. The schematic comparison test results according to ASTM C1609 *Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete*[4] shows much higher tensile strengths and greater ductility for ultra-high-performance concrete (UHPC) than for conventional concrete (CC). Figure: e.construct.

is minimal compared to the resistance provided by the prestressing strands. A major benefit of using UHPC is its shear resistance. It is conservative to assume that UHPC with steel fibers has a nominal shear resistance equivalent to about 0.75 ksi. The 0.75-ksi shear resistance is a conservative design value for UHPC mixtures that meet the following minimum flexural performance requirements as determined using ASTM C1609:

- A tensile strength of 1.5 ksi at first cracking;
- a tensile strength of 2 ksi at peak load;
- a peak load ≥ 125% of first-cracking load;
- a tensile stress at *L*/300 deflection ≥ 90% of stress at first cracking; and
- a tensile stress at *L*/150 deflection ≥ 75% of stress at first cracking,

where *L* is the span length of the specimen being tested.

Multiple structural benefits are realized when these minimum UHPC requirements are met for prestressed UHPC elements. First, because shear resistance of CC is typically on the order of 0.10 ksi to 0.40 ksi, and the shear resistance provided by stirrups is about the same, stirrups may not be necessary in beams using UHPC. Second, end-zone bursting cracks in pretensioned elements are better controlled with UHPC due to the presence of fibers. Finally, long-term camber growth is virtually nonexistent in UHPC beams because creep is a fraction of that in CC, especially when UHPC-specific thermal curing is introduced (heating to 194°F at 100% humidity for 48 hours within 14 days of transfer).

Examples of Current Conventional Concrete Double Tees

Bridge DTs have been in use for several decades. They are distinguished from

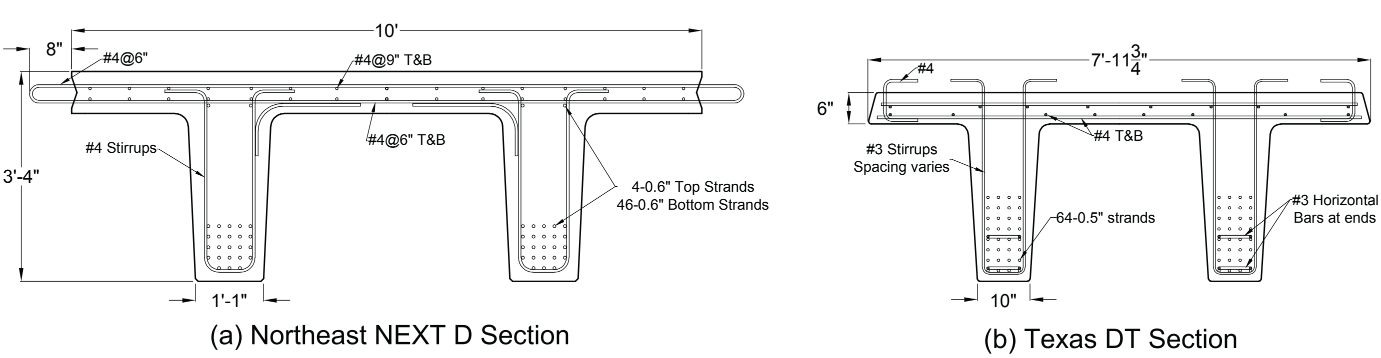


Figure 3. Standard sections for (a) NEXT D and (b) Texas double-tee beams. Figure: PCI Northeast and Texas Department of Transportation.

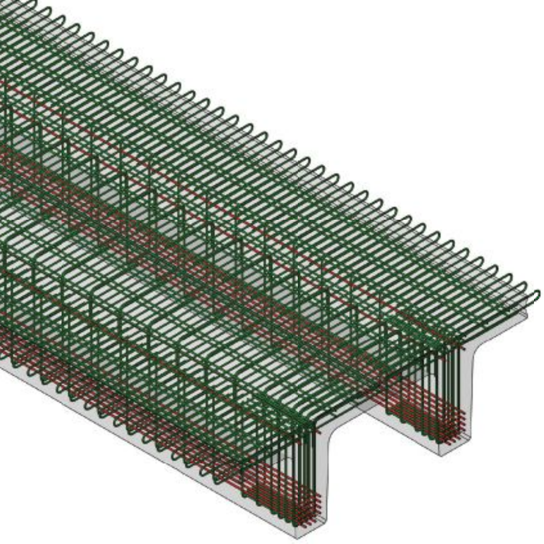


Figure 4. Isometric view of the end of a typical NEXT D beam designed using conventional concrete. Reinforcing bars and prestressing strands are shown. Figure: e.construct.

building DTs, often used in parking structures, by relatively wide stems and a relatively thick top flange. The primary advantage of bridge DTs is ease of fabrication—self-stressing forms, which have no moving parts, can be used. The DTs are stable and require no bracing during handling, storage, and erection. However, a bridge DT may weigh as much as 1 ton per foot of length, possibly creating significant handling, transportation, and erection challenges.

The Northeast Extreme Tee (NEXT) D beam developed by PCI Northeast[5] and a DT that has been used in Texas (**Fig. 3**) are the focus of the comparison featured later in this article. (Note: The Texas DT section has been archived and details cannot be accessed online.) The two sections shown in the figure represent the deepest and widest products for each type of DT.

The NEXT D beam can accommodate 46 bottom strands and 4 top strands—all 0.6 in. diameter. The NEXT D beam has an 8-in.-thick top flange, which can vary in width from about 8 to 10 ft and may be covered with a 2- to 3-in.-thick asphalt overlay. The beam weight for a 10-ft-wide and 40-in.-deep section is 1936 lb/ft. With a concrete compressive strength f_c' of 10 ksi, the span capacity of the 40-in.-deep NEXT D beam is 80 ft. This maximum span can be increased somewhat with more strand debonding at the ends than the customary 25% to 35% limit. For the 80 ft span, thirty-eight 0.6-in.-diameter strands are required in the bottom and the total piece weight is over 77 tons. **Figure 4** offers an isometric view of the end of a NEXT D beam designed using CC with reinforcing bars and prestressing strands shown. Note the quantity of reinforcing bars in the beam.

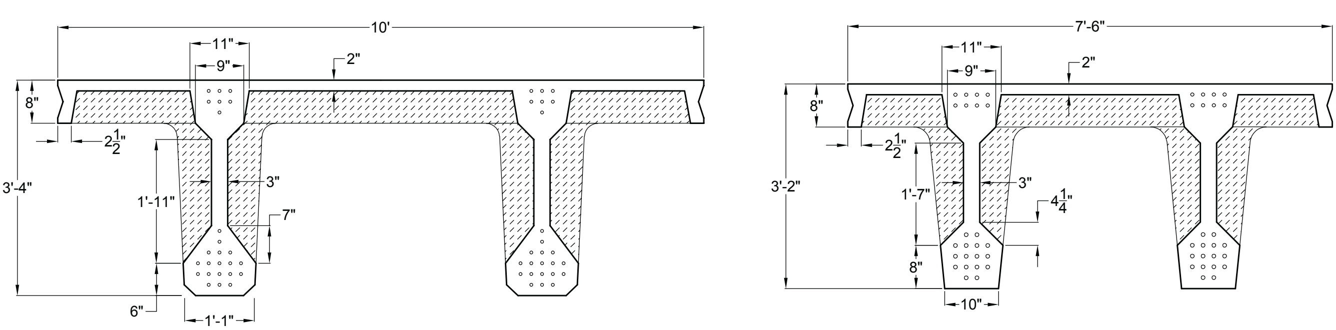
The cross-sectional area of the Texas DT is 1283 in.^{2} and the weight is 1336 lb/ft for an 8 ft width. For this analysis, a maximum of eight 8-strand rows, for a total of sixty-four 0.5-in.-diameter strands, are used. The midspan section is the focus of the study with the assumption that, as allowed in Texas, adequate strand draping and/or debonding is provided to satisfy stress limits at the member ends. The Texas DT shape has a 6-in.-thick top flange, which may be topped with a 5-in.-thick composite cast-in-place concrete topping. It may also be covered with a 2-in.-thick noncomposite wearing overlay for secondary road applications. In this example, the composite system is used. With a 10-ksi concrete compressive design strength and a 5-ksi topping, the span capacity of the CC beam is 85 ft. The precast concrete beam weight is 57 tons. Note that the assumed live load distribution factor is 0.7 for the Texas beam and 1.0 for the NEXT D beam; the difference in these factors is due to the different top flange widths.

Optimized Double-Tee Beams Using UHPC

For each of the two types of DT beams discussed above, an optimized UHPC section was developed. The optimized design was developed so that the current DT beam forms can be used. This is accomplished by inserting blockouts in the existing forms to create a bulb-tee shape in each stem. The resulting sections are similar to the previously described π-shaped beams used in France and Iowa, except that the top flange is also optimized using a ribbed slab. **Figure 5** shows the optimized section shapes using blockouts (hatched area) placed within the standard forms. The blockouts would be removed after the product is stripped from the forms. **Figure 6** provides an isometric view of the optimized NEXT D beam designed using UHPC. Note the significant reduction in reinforcing bars compared to the section with a CC design in Fig. 4. **Figure 7** is an isometric view from below the beam that shows the ribbed deck of the optimized NEXT D beam. The corresponding shape for the Texas beam is similar but is not shown here.

Three sample analyses were performed on the NEXT D beam:

- A CC beam with the dimensions shown in Fig. 3a, an 80-ft span and 38 bottom strands, with the top tensile stress at transfer at the ends limited to 0.20 ksi to eliminate potential cracking of the top face of the member;
- a UHPC beam with the dimensions as shown in Fig. 5a, an 80-ft span to match the CC beam span capacity, and a strand pattern with 30 bottom strands and 12 top strands; and
- a UHPC beam with the dimensions and prestressing strands as shown in Fig. 5a and a 90-ft span.



(a) Optimized NEXT D Beam

(b) Optimized Texas DT Beam

Figure 5. Optimized UHPC shapes for (a) NEXT D beam and (b) Texas double-tee beam based on standard beam shapes with form blockouts. These optimized UHPC illustrative shapes use about 50%–60% of the conventional concrete volume. Figure: e.construct.

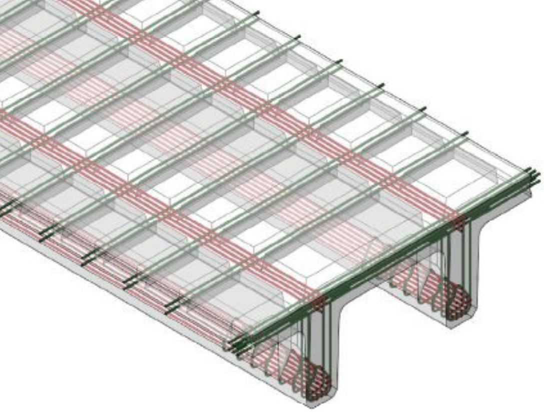


Figure 6. Isometric view of the end of the optimized UHPC twin-stemmed beam from above. Reinforcing bars and prestressing strands are shown. Figure: e.construct.

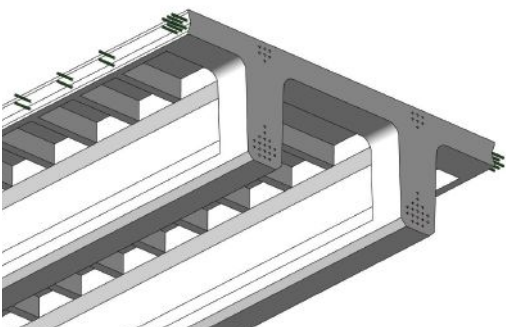


Figure 7. Isometric view of the end of the optimized UHPC twin-stemmed beam from below showing the ribbed deck and solid end block. Figure: e.construct.

Table 1 summarizes the input and output for the three cases. As shown, it is possible to reduce the weight per unit length by about 50% when UHPC is used. The 80-ft-span CC piece weighs about 77 tons, whereas the 80-ft-span UHPC piece weighs about 37 tons, which is 48% of the CC beam weight; a 90-ft-span UHPC piece weighs about 41 tons. Table 1 illustrates that adding more 0.6-in.-diameter strands to the UHPC design can result in a 10 ft increase in the possible span length. A design span of nearly 100 ft can be achieved with 0.7-in.-diameter strands (results not shown in table), which the authors recommend to obtain the greatest value from using UHPC. However, deflections and vibrations become more critical with relatively large span-to-depth ratios. Please note that in all three cases, the beam spacing and beam width are taken to be the same to simplify the comparison.

The absence of reinforcing bars, as allowed by the UHPC design, significantly reduces labor costs in design, detailing, production, and inspection. The authors' analysis for these beams shows no need for bursting or bottom-flange confinement reinforcement. However, a nominal amount is recommended as a conservative measure until further research shows whether reinforcement can be totally eliminated without objectionable cracking.

If UHPC and no. 6 reinforcing bars or smaller are used in the top flange ribs in the transverse direction, the longitudinal joint between beams can be as narrow as 6 in. This detail follows the FHWA recommendations[6] that a bar development length in UHPC can be as short as 8 bar diameters. Please note that the number of bottom strands in the UHPC beam is less than that for a CC beam of the same span. However, it may be desirable to place more strands in the top, primarily to limit camber.

A similar study was performed on the Texas DT, but the results are not listed in the table. The Texas DT shape, modified as shown in Fig. 5b, was analyzed without a composite cast-in-place topping but with a 3-in.-thick noncomposite asphalt overlay and compared to the 85-ft span Texas DT beam using CC and the composite topping previously described. Using the same concrete properties as the UHPC twin-stemmed beam example in Table 1, the Texas DT UHPC member can span 95 ft with thirty-two 0.7-in.-diameter bottom strands and sixteen 0.7-in.-diameter top strands. No draping or debonding is required. The weight of the optimized beam is reduced to 795 lb/ft (38 tons), which is 40% lighter than the CC beam used for comparison; this reduced weight does not include the additional reduction from using an asphalt wearing surface instead of a composite cast-in-place topping.

Table 2. Comparison of CC and UHPC Beam properties

Section	Area, in.^{2}	I_x, in.^{4}	y_b in.
NEXT D CC	1,882	260,900	26.5
NEXT D UHPC	789	170,600	24.4
Texas DT CC	1,280	147,800	23.4
Texas DT UHPC	690	128,700	22.8

Details at the ends of the UHPC DT beams will need investigation, especially if the end is skewed. A short length at the ends of the DT beams may be made with an 8 in. full-thickness top flange.

Table 1. Comparison of NEXT D Beam designed with CC and the optimized UHPC twin-stemmed beam designs

Parameters	CC beam, 80-ft span	UHPC beam, 80-ft span	UHPC beam, 90-ft span
Concrete compressive strength at transfer (ksi)	8	10	10
Concrete compressive strength at service (ksi)	10	18	18
Specified peak tensile strength (ksi)*	—	2	2
Flange width (ft)	10	10	10
Member depth (in.)	40	40	40
Unit weight of concrete (lb/ft^3)	150	155	155
Beam weight (lb/ft)	1936	920	920
Number of bottom 0.6-in.-diameter strands (both webs)	38	30	36
Number of top 0.6-in.-diameter strands (both webs)	4	12	14
Total number of 0.6-in.-diameter strands	42	42	50
Design span (ft)	80	80	90
Bottom-fiber tensile stress limit at Service III (ksi)	0.60	1.00	1.00
Computed bottom-fiber tensile stress at Service III (ksi)	0.44	0.94	1.00
Moment demand at Strength I (ft-kip)	6110	5305	6064
Moment capacity (ft-kip)	6174	5389	6074
Shear strength demand at Strength I at critical section (kip)	294	249	258
Design shear capacity at critical section (kip)	520†	362‡	362‡
Estimated camber at midspan at transfer (in.)	1.18	1.26	1.93
Live load deflection at midspan (in.)	–0.70	–0.89	–1.00

*Peak tensile strength as determined using ASTM C1609.[4] Not required for CC design.
†With two legs of no. 4 shear stirrup reinforcement in each stem spaced at 12 in. on center for beams with straight strands.
‡With no shear stirrup reinforcement.

This solid top flange could also be useful if there is a desire to make beams continuous for live load because it allows placement of longitudinal continuity bars at the piers.

Cost Estimates

An approximate cost analysis was performed for the NEXT D beam example. Results would be similar for the Texas beam. The CC beam weighs 1936 lb/ft, corresponding to a volume of concrete of 0.48 yd^3/ft. The corresponding values for the UHPC beam are 920 lb/ft and 0.20 yd^3/ft. Assuming an average cost per cubic yard of the 10-ksi concrete is $150, and cost of shear reinforcement, strands, equipment, labor, and other expenses is $600, the total product cost becomes $750/$yd^3$, or $360 per foot of beam for the CC beam. If using UHPC increases the cost of concrete from $150 to $800, and the other costs are the same, the total cost becomes $1,400/$yd^3$, but only $280 per foot of beam for the UHPC beam, resulting in overall savings. Note that actual savings associated with UHPC could be even greater when one considers additional benefits, such as not having to design, detail, purchase, place, and inspect the shear reinforcement required in the CC beam, or the additional benefits associated with lighter beam weight such as shipping, handling, and foundation design. This analysis is approximate. Unit costs vary significantly from one area of the United States to another.

Conclusion

The analysis presented in this article shows that, based on the initial findings of the PCI-funded UHPC implementation project, it is possible to have a cost-effective UHPC alternative to the popular DT beams, whose primary drawback is their heavy weights, which may limit span capacities. For the same depth and amount of prestressing force, one can realize a longer span with a significantly reduced weight and near elimination of reinforcing bars. The authors believe that the UHPC option is cost-competitive on a first-cost basis and is much more valuable than the CC design when life-cycle costs are compared. UHPC, with its extremely low permeability and excellent durability properties, is expected to significantly extend the service life of bridges.

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EDITOR'S NOTES

See Resources tab on the ASPIRE *website for additional information concerning these engineering computations.*

See the Concrete Bridge Technology article in the Spring 2017 issue of ASPIRE *for more information on the use of UHPC for precast concrete bridge girders in Malaysia, which sparked great interest in realizing the potential benefits of UHPC in the United States.*