Structural Design with Ultra-High-Performance Concrete

by Dr. David Garber, Dr. Rafic G. Helou, and Dr. Benjamin Graybeal, Federal Highway Administration

Ultra-high-performance concrete (UHPC) is a portland cement–based composite material that includes supplementary cementitious materials (SCMs), fine sand, water, steel fibers, high-range water-reducing admixture, and other admixtures as needed. The rheology of UHPC can be customized to be anywhere from self-consolidating (ideal for casting connections and components in formwork) to thixotropic (ideal for casting bridge deck overlays on cross slopes and grades).

UHPC is concrete with enhanced mechanical properties. In accordance with the American Association for State Highway and Transportation Officials' (AASHTO's) recently released *Guide Specifications for Structural Design with Ultra-High Performance Concrete*,[1] a concrete mixture must have steel-fiber reinforcement and achieve the following characteristics to be classified as a UHPC material:

- A minimum compressive strength f'_c of 17.5 ksi
- A minimum effective cracking strength $f_{t,cr}$ of 0.75 ksi
- A minimum crack localization strength $f_{t,loc}$ equal to or greater than the effective cracking strength $f_{t,cr}$
- A minimum crack localization strain $\varepsilon_{t,loc}$ of 0.0025

UHPC is much more durable than conventional concrete. The chloride ion penetrability of UHPC, measured in accordance with ASTM C1202,[2] can be as low as 50 coulombs (compared to 1500 to 2500 coulombs for conventional concrete). The relative dynamic modulus (RDM) of UHPC, measured in accordance with the standard test method for freeze-thaw resistance (formerly ASTM C666[3]) can be greater than 95% (compared to RDMs of 75% to 80% for conventional concrete). These properties demonstrate that UHPC has very low permeability and is highly resistant to freezing and thawing.

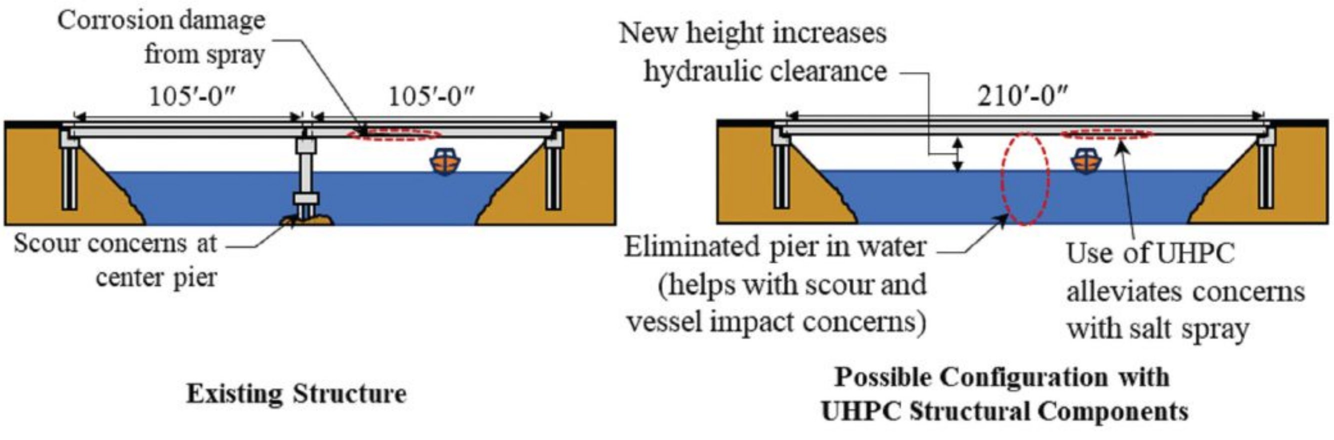
To date, UHPC has been primarily used for connections between prefabricated concrete elements and for preservation and repair activities (including deck overlays, link slabs, and beam end repairs).[4] However, AASHTO's *Guide Specifications for Structural Design with Ultra-High Performance Concrete* now enable owners and engineers to design structural components, leveraging the full potential of UHPC.

Benefits of UHPC Structural Components

UHPC structural components can be designed to be more efficient and have higher strengths than conventional concrete components. Therefore, engineers can leverage UHPC to design superstructures with several structural benefits, including the following:

- Decreased superstructure weight. When UHPC is used instead of conventional concrete, superstructures can be constructed with lighter sections and wider beam spacing, which can result in significantly lighter superstructures. As a result, it may be feasible to reuse a substructure in situations where reuse was not previously possible, and substructure costs may be reduced.
- Shallower superstructure depths. UHPC superstructures can be shallower than conventional concrete alternatives for similar span lengths, which can help state departments of transportation and other agencies alleviate

Figure 1. Side-by-side comparison of a conventional structure and a hypothetical structure where ultra-high-performance concrete structural components can be used to eliminate the center pier and increase hydraulic clearance. All Figures: Federal Highway Administration.



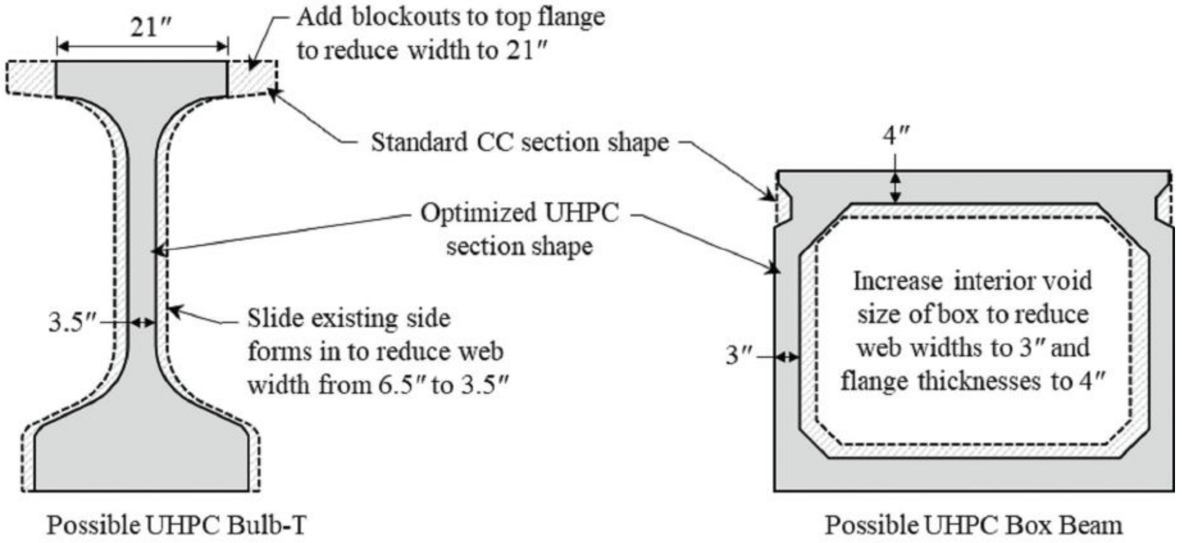


Figure 2. Ultra-high-performance concrete (UHPC) section shapes are optimized by modifying the existing formwork for conventional concrete (CC) standardized shapes.

challenges involving low vertical clearance and bridge collisions. Bridge owners could also benefit from greater hydraulic clearance.

- Increased span lengths. UHPC superstructures can be designed to have longer spans than conventional concrete alternatives at similar section depths. As a result, it may be possible to eliminate interior piers in waterways (**Fig. 1**) or shoulder piers that are immediately adjacent to traffic. These design changes can extend a bridge's service life and potentially resolve other structural integrity and safety concerns.

Garber et al.[5] quantified these benefits in several case studies.

Figure 2 illustrates that cross sections for UHPC components can be optimized to be more than 25% lighter than conventional concrete components—even considering UHPC's higher unit weight—and they can span lengths more than 25% longer than those spanned by conventional concrete sections of similar depths.[1,6,7] These optimized section shapes can be constructed with simple modifications to formwork used for standard conventional concrete shapes.

UHPC section depths can be more than 12.5% shallower than the depths of conventional concrete components for similar span lengths, and UHPC superstructures can be designed to be 41% lighter for a 120-ft span and 68% lighter for a 30-ft span.[5]

UHPC structural components will also have longer service lives than conventional concrete alternatives, leading to lower service-life costs for UHPC structures.[8] An extended service life can be beneficial for structures on routes with high volumes of average daily traffic, routes in remote areas with long detours, or bridges of high importance (for example, adjacent to hospitals). Many other benefits to using UHPC structural components are summarized in Garber et al.[7] and Graybeal and Helou.[6]

Design of UHPC Structural Components

In many ways, the design of UHPC structural components mirrors the design of conventional concrete. An engineer who understands the process and procedures of designing a conventional concrete structural component will be able to understand the procedures for designing a UHPC structural component. Some of the differences in the design process are highlighted in this section.

One of the primary benefits of UHPC is its post-cracking strain capacity in tension. The design of UHPC structural components requires an engineer to return to the fundamentals of engineering mechanics and use strain-based design approaches. The strain-compatibility approach is used for calculating the nominal flexural resistance (with or without axial force), where a linear strain profile across the section depth is used with idealized stress-strain material relationships and equilibrium principles to calculate the neutral-axis depth and associated moment and curvature values.[6,7,9] (See the "Strain Compatibility Primer" articles in the Fall 2024 and Winter 2025 issues of *ASPIRE*® to learn more about the strain-compatibility approach.) An alternate strain-based shear design approach was developed for AASHTO's *Guide Specifications for Structural Design with Ultra-High Performance Concrete* based on the same concepts as the modified compression field theory developed for conventional concrete (see El-Helou and Graybeal[10]).

Many other aspects of the design of UHPC structural components are similar to the design of conventional concrete components. However, there are slight differences, including prestress loss calculations (with different equations for calculating creep and shrinkage), service stress checks (with different tensile stress limits), principal stress checks in the web (required for all UHPC components), and fatigue stress checks (required for embedded steel in UHPC components). Additionally, slenderness effects and girder stability may need to be considered for the longer, more slender members that are made possible with UHPC. More details on the design of UHPC structural components can be found in Garber et al.,[7] Murphy and Bayrak,[11] and Graybeal and Helou.[6]

Available Resources and Workshop

The Federal Highway Administration (FHWA) has recently published several resources to assist state transportation agencies, engineers, contractors, and other stakeholders in implementing UHPC structural components. These include the following reports:

- *Structural Design with UHPC Workshop Manual* (FHWA-RC-24-0006)[7]
- *Structural Design with Ultra-High Performance Concrete* (FHWA-HRT-23-077)[6]
- *Possible Framework for Using the Strut-and-Tie Method (STM) with Ultra-High Performance Concrete (UHPC)* (FHWA-RC-24-0004)[12]
- *Section Shapes for Short-Span UHPC Bridges* (FHWA-RC-24-0009)[5]

FHWA has also developed a one-day workshop to help with the implementation of UHPC structural components. The workshop builds on basic knowledge of reinforced and prestressed concrete bridge design, and introduces and explains aspects of analysis and structural design that are unique for UHPC structural components. The learning objectives for the workshop include the following:

- Identify when using UHPC will be advantageous.
- Describe the differences between conventional concrete and UHPC related to the design of structural elements.
- Analyze and design UHPC structural elements using *Structural Design with Ultra-High Performance Concrete* (FHWA-HRT-23-077).[6]

State departments of transportation interested in implementing UHPC structural components in the near future may contact David Garber (david.garber@dot.gov) for more information on the workshop.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2024. *Guide Specifications for Structural Design with Ultra-High Performance Concrete*. Washington, DC: AASHTO.
2. ASTM International. 2022. *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.* ASTM C1202-22e1. West Conshohocken, PA: ASTM International.
3. ASTM International. 2015. *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Withdrawn 2024).* ASTM C666/C666M-15. West Conshohocken, PA: ASTM International.
4. Federal Highway Administration (FHWA). 2024. "Deployments of UHPC in Highway Bridge Construction. Interactive Map." https://highways.dot.gov/research/structures/ultra-high-performance-concrete/deployments.
5. Garber, D., R. Helou, and B. Graybeal. 2024. *Section Shapes for Short-Span UHPC Bridges*. FHWA-RC-24-0009. Washington, DC: FHWA.
6. Graybeal, B., and R. Helou. 2023. *Structural Design with Ultra-High Performance Concrete.* FHWA-HRT-23-077. McLean, VA: FHWA. https://highways.dot.gov/sites/fhwa.dot.gov/files/FHWA-HRT-23-077.pdf.
7. Garber, D., R. Helou, and B. Graybeal. 2024. *Structural Design with UHPC Workshop Manual.* FHWA-RC-24-0006. Washington, DC: FHWA. https://www.fhwa.dot.gov/resourcecenter/teams/structures-geotechnical-hydraulics/Structural_Design_UHPC_Workshop_Manual.pdf.
8. Haber, Z., M. McDonagh, A. Foden, S. Sadasivan, and B. Graybeal. 2023. *Ultra-High Performance Concrete (UHPC) Overlays: An Example of Lifecycle Cost Analysis.* FHWA-HRT-23-012. McLean, VA: FHWA. https://highways.dot.gov/sites/fhwa.dot.gov/files/FHWA_HRT-23-012.pdf.
9. El-Helou, R. G., and B. A. Graybeal. 2022. "Flexural Behavior and Design of Ultrahigh-Performance Concrete Beams." *Journal of Structural Engineering* 148 (4). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003246.
10. El-Helou, R. G., and B. A. Graybeal. 2023. "Shear Design of Strain-Hardening Fiber-Reinforced Concrete Beams." *Journal of Structural Engineering* 149 (2). https://doi.org/10.1061/JSENDH.STENG-11065.
11. Murphy, T., and O. Bayrak. 2024. "Development of the *AASHTO Guide Specifications for Ultra-High-Performance Concrete*." *ASPIRE* 18 (1): 16–17. https://doi.org/10.15554/asp18.1.
12. Garber, D., R. Helou, and B. Graybeal. 2024. *Possible Framework for Using the Strut-and-Tie Method (STM) with Ultra-High Performance Concrete (UHPC).* FHWA-RC-24-0004. Washington, DC: FHWA. https://www.fhwa.dot.gov/resourcecenter/teams/structures-geotechnical-hydraulics/FHWA-RC-24-0004.pdf.