Guide Specifications for Structural Design with ULTRA-HIGH PERFORMANCE CONCRETE

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Cover images, clockwise from top: A pretensioned UHPC bridge girder at the FHWA Turner-Fairbank Highway Research Center, courtesy of Rafic Helou, Federal Highway Administration. Pretensioned UHPC girders in the Mars Hill Bridge in Wapello County, Iowa, courtesy of Benjamin Graybeal, Federal Highway Administration. Pretensioned UHPC girders in the Cat Point Creek Bridge near Warsaw, Virginia, courtesy of Benjamin Graybeal.

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FOREWORD

These Guide Specifications are the result of extensive research carried out by the Turner Fairbank Highway Research Laboratory of the Federal Highway Administration (FHWA), the Precast/Prestressed Concrete Institute, and others over a period of years, and represent the current state of knowledge regarding the application of ultra-high performance concrete (UHPC) to bridge design. Two design examples have been developed by the FHWA and are contained in the report FHWA-HRT-23-077: *Structural Design with Ultra-High Performance Concrete* (Graybeal and Helou, 2023). While the 2023 FHWA publication was the basis for these Guide Specifications and contains similar design provisions, these Guide Specifications are not identical and are intended to be used independently of that document. It is intended that these Guide Specifications will be used in conjunction with material specifications that include requirements for qualification and acceptance testing of UHPC materials. Until such time as material specifications are published by AASHTO, Owners and Designers can use the 2023 FHWA publication, which contains a material conformance framework. Guidance on the fabrication of precast components with UHPC can be found in the *Guidelines for the Use of Ultra-High-Performance Concrete (UHPC) in Precast and Prestressed Concrete* (TR-9-22) from the Precast/Prestressed Concrete Institute (PCI 2022).

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SECTION 1:

SCOPE

1.1—GENERAL

The provisions in these Guide Specifications apply to the design of bridge and ancillary structures and components constructed of ultra-high performance concrete (UHPC). UHPC shall be a portland cement composite with a discontinuous pore structure and reinforced with steel fiber reinforcement. Other non-steel fiber reinforcements may be included as supplements, but shall not be the primary fiber reinforcement.

The provisions are based on UHPC materials that conform to requirements for qualification and acceptance testing, exhibit a strain-hardening behavior, and have the following minimum property values for use in design determined according to Section 4:

- 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, $f_{t,loc}$, greater than or equal to the effective cracking strength, $f_{t,cr}$; and
- A minimum crack localization strain, $\varepsilon_{t,loc}$, of 0.0025.

The recommendations of these Guide Specifications are not intended to supplant proper training or the exercise of judgment by the Designer. They state only the minimum requirements necessary to provide public safety. The Owner or the Designer may require the sophistication of the design or the quality of materials and construction, or both, to be higher than the minimum requirements.

Consideration shall be given to the durability performance of the UHPC mix selected.

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UHPC is a class of concrete that has emerged as a compelling material for use in the design, construction, and preservation of structures. It is a versatile material that can be used in primary structural components, field-cast connections between prefabricated components, and repair applications. As with conventional concrete, UHPC is composed of inert and reactive constituents that, when combined with water and chemical admixtures, undergo a hydration reaction to transform from a semi-fluid mixture into a competent structural material.

As defined herein, UHPC is a strain-hardening, steel fiber-reinforced concrete, meaning that this type of concrete can resist tensile loads beyond cracking of the cementitious composite (Graybeal, 2015b). Engagement of this tensile response in structural design necessitates a reconsideration of some of the fundamental behavioral assumptions associated with conventional reinforced concrete.

UHPC-class materials have been demonstrated to deliver significantly enhanced durability compared with conventional concretes (Haber et al., 2018). Formulations that meet the performance requirements have been demonstrated to have reduced permeability and thus are more resistant to liquid permeation and associated degradation mechanisms. UHPC materials that conform to the requirements for qualification and acceptance testing should also meet durability requirements set by the Owner. Based on the work of Spragg et al. (2022), Graybeal and Helou (2023) proposed a durability threshold value of 1,500 Ω·m for UHPC, using a modified version of the AASHTO TP 119-22 test method. PCI (2022) recommends a combination of test methods be used to characterize the durability of UHPC mixtures. The above methods can be used to establish threshold limits for durability.

There is no standard mixture for UHPC. This class of concrete is defined through prescriptive and performance requirements stated herein. UHPC materials should conform to the requirements for qualification and acceptance testing that consider the statistical variability of the material properties and ensure design properties that are 1.5 standard deviations below the mean values. UHPC commonly contains a high concentration of steel fiber reinforcement, generally near or greater than 2 percent per volume. UHPC also commonly contains supplementary cementitious materials and graded inert fillers. UHPC rarely contains coarse aggregate. A mix may include additional, supplementary non-steel fibers, but cannot supplant steel fiber reinforcement with non-steel fibers.

An extensive research program was completed by the Precast/Prestressed Concrete Institute (PCI) (e.Construct USA, 2021) which focused on developing specific UHPC mixtures and processes best suited for production of precast, prestressed bridge girders in traditional precasting facilities. Steel fibers, either 0.5 in. or 0.75 in. long at a 2 percent by volume content, are used. The minimum properties of UHPC provided by PCI differs from that adopted herein, as follows:

- A minimum compressive strength, f'_c, of 17.4 ksi,
- A minimum first-peak (first crack) strength of 1.5 ksi,
- A minimum peak (ultimate) strength of 2.0 ksi,
- A minimum ratio of peak (ultimate) strength to first-peak (first crack) strength of 1.25, and
- A minimum residual strength of 75 percent of the first-peak strength when the net deflection reaches $L/150$, where L is the span length or distance between the supports (in.).

The strengths and deflections referenced in the last 4 bullets of the previous list are based on ASTM 1609-19A prism flexural tests. For further details, see PCI (2022).

1.2—DESIGN PHILOSOPHY

The guidance in these Guide Specifications is based on limit state design principles where structural components shall be proportioned to satisfy the requirements of all appropriate limit states.

Refer to *AASHTO LRFD Bridge Design Specifications* (AASHTO LRFD) for provisions on limit state design principles, general design and location features, and structural analysis and evaluation. All references to AASHTO LRFD are in reference to the 9th Edition.

The serviceability and strength provisions herein are based on the observed and anticipated performance of example UHPC-class materials when configured for, and subjected to, structural loading. In general, fundamental structural behaviors (e.g.,

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tension, compression, flexure, shear) are treated based on the intersection of the principles of engineering mechanics and the performance of UHPC. In situations where the performance of UHPC is expected to significantly outperform conventional concrete and there is a lack of specific UHPC test results, AASHTO LRFD provisions for conventional concrete may have been adopted.

The tensile behavior of UHPC at crack localization is of critical importance. Beyond the crack localization strain, the UHPC offers decreasing tensile resistance, causing loads to be shed to available alternate load paths. In general, crack localization within a UHPC structural element results in concentrated deformations (e.g., wide cracking, flexural hinging) that are to be avoided.

Crack localization refers to a point in the tensile stress–strain response of UHPC where the tensile deformation starts to accumulate into a single dominant crack and the tensile resistance starts to continuously decline without substantial recovery. Crack localization occurs when the fiber reinforcement bridging a crack debonds and starts to pull out of the cementitious matrix. In unreinforced members, crack localization coincides with a loss of member capacity. In reinforced members, the loss of the UHPC tensile resistance and the concentrated deformation at a single localized crack within the member cause local redistribution of the applied stresses, potentially straining the tensile reinforcement that bridges the crack beyond its capacity to resist. This reinforcement straining behavior is accentuated by the shorter length over which discrete reinforcements can be developed in UHPC and should be avoided.

The tensile resistance behavior of UHPC depends on the distribution and orientation of the fiber reinforcement in the UHPC. These provisions rely on the use of appropriate construction methods to ensure that the fiber reinforcement is evenly dispersed through the member and that adverse fiber orientation effects have been avoided.

Contract documents should require the use of appropriate construction methods. Disturbance of fiber distribution, as would occur at a cold joint or when fiber flow is restricted from reaching a part of the member, will affect the structural performance of the member. PCI (2022) has developed guidance for use of UHPC in the precast environment with consideration of fiber distribution and orientation.

1.3—LOADS AND LOAD COMBINATIONS

Refer to AASHTO LRFD for provisions on loads, load combinations, and load factors.

The provisions of AASHTO LRFD Table 3.5.1-1 shall be supplemented by Article 4.2.2 of these Guide Specifications, which defines the unit weight of UHPC.

1.4—LIMITATIONS

The provisions in these Guide Specifications shall not apply to:

- The non-UHPC portion of composite structural members, or

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These Guide Specifications do not provide guidance on the design of conventional concrete or structural steel portions of a member partially composed of UHPC. Refer to Section 5 and Section 6 of AASHTO LRFD for provisions applicable to these structural materials.

- The design of plastic hinge regions of components that are part of the earthquake resisting system in Seismic Zones 2, 3, or 4, as defined within AASHTO LRFD.

The provisions in these Guide Specifications do not address the provisions for specific structure components and types discussed in AASHTO LRFD Article 5.12.

The provisions in these Guide Specifications were not developed to address the special considerations and detailing inherent in post-tensioned structures.

These provisions were not developed for application in plastic hinge regions of elements.

This provision is not intended to prohibit use of post-tensioning with UHPC or the structure types listed in AASHTO LRFD Article 5.12; however, these items are not specifically addressed in these Specifications, and the guidance provided in AASHTO LRFD Article 5.12 may not necessarily apply to UHPC.