

Development of an AASHTO Guide Specification for Ultra-High Performance Concrete

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Abstract:

The widespread, growing interest in the United States in using ultra-high performance concrete (UHPC) in engineered structures is being hindered by a lack of structural design guidance relevant to this class of materials. The material characteristics that form the foundational inputs for existing reinforced concrete design specifications do not represent the behaviors that can be attained with UHPC; therefore, using existing design guidance results in inefficient, overly costly structures. The U.S. Federal Highway Administration has embarked on an effort to develop the needed design guidance for bridges. This document, which will be in the form of a guide specification and will supplement the AASHTO LRFD Bridge Design Specifications, is being coordinated with the relevant subcommittee of the AASHTO Committee on Bridges and Structures. The guide specification will define UHPC, present threshold mechanical and durability properties, define material models, and provide design guidance for flexure, shear, and other critical performance metrics. Both prestressed concrete and mild steel reinforced concrete elements will be covered. This paper discusses the framework for the guide specification and provides insight into key aspects that have been investigated and drafted to date.

Keywords:

ultra-high performance concrete; bridge; design; construction; specification; AASHTO; material performance models; structural performance models

1. Introduction

Knowledge of and experience with ultra-high performance (UHPC) inevitably leads to broader recognition of the opportunities that this class of materials presents. As experts and practitioners in a community of practice begin deploying UHPC solutions to address long-standing challenges, they must confront hurdles including the availability of UHPCs, the lack of fabrication and construction experience, and the perceived risk of engaging an innovative solution. One of the

largest hurdles is the lack of formal guidance covering the design of UHPC structures. The material characteristics of UHPC surpass those of conventional concrete. These characteristics form the foundational inputs for existing reinforced concrete design specifications; therefore, using existing design guidance results in inefficient, overly costly UHPC structures.

Since the first use of UHPC in a U.S. surface transportation structure in 2006, the bridge community has been steadily pressing forward with developing and refining UHPC solutions that address critical needs (Russel and Graybeal, 2013). Although more than 200 bridges in the U.S. have now been constructed or rehabilitated using UHPC, the large majority use UHPC in field-cast connections between prefabricated bridge elements. The use of UHPC in primary structural elements has been rare; for these elements, designers must rely on guidance emanating from research reports and/or non-domestic sources and thus they often hesitate and revert to the use of conventional construction materials.

To address this need, the U.S. Federal Highway Administration (FHWA) has embarked on an effort to develop the needed design guidance for bridges. Bridge design in the U.S. is reliant on the AASHTO LRFD Bridge Design Specifications (2017). This UHPC guidance will supplement the existing design specifications and its development is being coordinated with the relevant subcommittee of the AASHTO Committee on Bridges and Structures. It is anticipated that the UHPC guidance will be published by AASHTO in the form of a guide specification after thorough review by relevant experts.

The guide specification will define UHPC, present threshold mechanical and durability properties, define material models, and provide design guidance for flexure, shear, and other critical performance metrics. Both prestressed concrete and mild steel reinforced concrete elements will be covered. Efforts on this guide specification began in 2017 and progress, as summarized herein, continues to be made.

2. Background

UHPC structural design guidance has already been developed by various communities of practice around the world. Of note are the French, Swiss, and Canadian efforts, each of which has followed a distinct path. French guidance was first promulgated with the publication of SETRA-AFGC Interim Recommendations (2002). These recommendations were updated, refined, and expanded over the years until recently when they were recrafted as formal addendums to the Eurocode. These Eurocode specification addendums define UHPC (NF P18-710 2016), specify design procedures (NF P18-451 2016), and provide guidance on the construction of UHPC structures (NF P18-451 2018). These Eurocode addendums are arguably the most refined and complete UHPC specifications in the world.

The Swiss-based guidance was first published in 2016 (SIA 2052). This guidance, containing less detail than the French guidance, serves a similar purpose through a different framework. Instead of providing significant guidance and detail throughout the design process, the Swiss guidance instead provides general principles of behavior and has a greater reliance on the experience and expertise of the designer. As such, this guidance may be easier for an expert to quickly understand but is harder for a novice to utilize.

The Canadian-based guidance has been under development for the past three years and, given the similarities between U.S. and Canadian structural design practice, may be the closest analog to guidance under development in the U.S. The Canadian Standard Association (CSA) supported the volunteer development of the guidance which will be delivered as a pair annexes to the existing Canadian standards. The first annex will supplement CSA A23.1 *Concrete Materials*

and Methods of Construction (2014); it defines UHPC and test methods relevant thereto. The second annex will supplement the CSA S6 Canadian Highway Bridge Design Code (2014). This annex provides structural design guidance for fiber reinforced concrete with a focus on UHPC. Both annexes are expected to be published in 2019 along with the newest versions of the parent documents.

3. Guidance Development Process

The anticipated AASHTO guide specification for UHPC will be developed in a manner similar to that used for other emerging technologies. Once a technology shows sufficient promise that it captures the sustained attention of a relevant AASHTO committee, the committee will entertain the initial drafting of a technical guidance aimed at supporting the use of the technology by the community. This guidance will be drafted outside of AASHTO's formal committee structure; however, the committee will remain aware of and will become increasingly engaged with the effort as the draft guidance nears completion.

In the present case, the UHPC experts in the FHWA research branch are leading the effort to draft the guide specification. The AASHTO committee that manages the structural concrete design aspects of the LRFD Bridge Design Specifications (i.e., AASHTO T-10) is being periodically briefed and is offering feedback on the guide specification development. The model for completion of this guidance relies on engagement of the broader community of experts. FHWA is beginning to engage UHPC and concrete bridge design experts, and anticipates that greater levels of feedback will occur as the guidance passes key milestones.

4. Anticipated Guidance Content

It is anticipated that the UHPC guide specification will cover five key topics: 1) introduction and definition, 2) material properties, 3) structural design, 4) construction, and 5) promising applications. Given both the breadth of potential UHPC applications and existing conventional concrete structural design guidance, the UHPC guide specification will not be able to fully parallel existing design specifications. Extension of the guidance will occur in time as both knowledge and demand increase. The following descriptions of guidance content are based on current expectations and they may change as the guidance is refined and approaches publication.

4.1. Introduction

A key starting point for any specification is a delineation of the scope of the document and the definition of fundamental parameters. The FHWA defines UHPC as follows (Graybeal 2011):

UHPC is a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement. In general, the mechanical properties of UHPC include compressive strength greater than 21.7 ksi (150 MPa) and sustained postcracking tensile strength greater than 0.72 ksi (5 MPa). UHPC has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability compared to conventional concrete.

It must be recognized that, as with conventional concrete, there are myriad ways to create a UHPC. However, in order to use this guidance, the material must express certain key performance

attributes. The three key performance measures identified in the definition are compressive strength, tensile response, and enhanced durability. Similar materials whose performance falls outside of this guidance may have very compelling applications but might not perform appropriately if used in structural elements designed according to this guidance.

To appropriately engage the properties of UHPC in structural design, it must be recognized that the stress-strain response of UHPC differs from conventional concrete and that strain is a critical part of any UHPC structural design. The use of closed-form, strength-based equations to predict performance will often not be possible because the design will be founded upon first principles wherein stresses on strained cross sections will be summed. Assumptions related to concrete only carrying compression and the resulting formulaic simplifications are generally not appropriate for UHPC.

4.2. Material Properties and Models for UHPC

The compressive mechanical response of concrete is central to any concrete structural design guidance. UHPC differs from conventional concrete in that the mechanical response offers an increased modulus of elasticity, an increased compressive strength, a more linear pre-peak stress-strain response, and an increased strain at ultimate strength. Given that UHPC structural design is more heavily reliant on the stress-strain response of the material, a model that conservatively predicts the compressive response is needed.

Figure 1 provides example of an experimental UHPC compressive response as well as an illustration of a compressive response model. The elastic plastic model is observed to nearly mimic the experimental result from the initiation of loading until the stress reaches α times the compressive strength. At this point, the model response sustains this compressive resistance until the strain at the material’s compressive strength is reached.

This elastic-plastic model requires only the compressive strength, f'_c , the elastic modulus, E_c , and the strain at peak strength, ϵ_{cu} . The compressive strength would be specified as part of the project requirements, and the material performance would be verified through the execution of ASTM C1856 (2017). Although the elastic modulus and the strain at peak strength could be specified and verified through testing, they would normally be calculated as a function of the compressive strength. Equation 1 provides a predictive relationship for elastic modulus of UHPC (Graybeal 2019). The strain at peak strength can be assumed to be 0.0035.

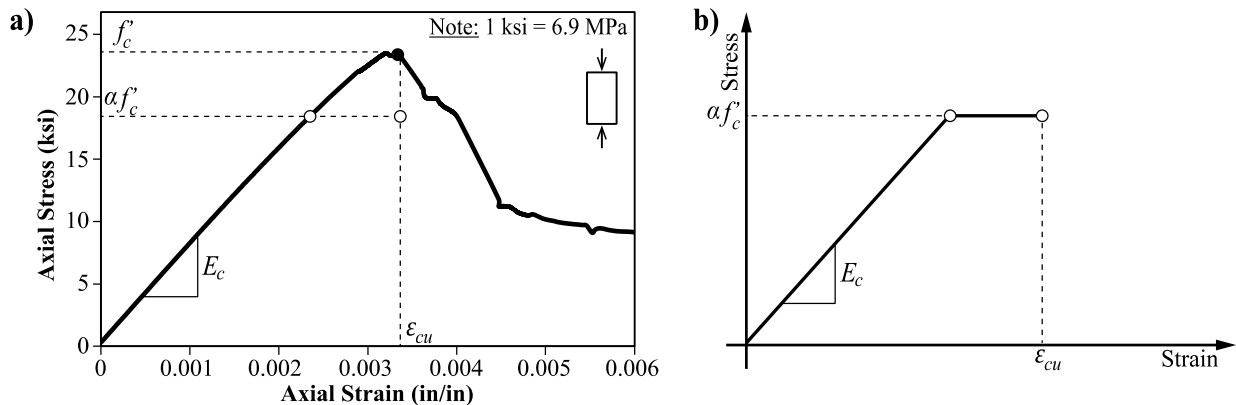


Figure 1. (a) Experimental compressive response and (b) Compressive stress-strain model for UHPC

$$E_c = 1,550\sqrt{f'_c} \text{ in ksi units} \quad (\text{Eq. 1})$$

The tensile mechanical response of UHPC is fundamentally different from that of conventional concrete. By definition, UHPC offers sustained post-cracking tensile mechanical resistance. This tensile resistance is commonly engaged in design to resist loads applied to the structure. Therefore, the model of the tensile response must conservatively predict performance from initial elastic loading, through cracking, and to a predefined tensile strain limit.

Figure 2 provides an example of an experimental UHPC tensile response as well as an illustration of a tensile response model. The experimental response is obtained through direct capture of tensile load and strain response on a known cross-section during a fixed-end, uniaxial, displacement-controlled test. FHWA developed an appropriate test method for directly capturing the needed information (Graybeal and Baby, 2013). The use of indirect tensile test methods which inherently rely on user assumptions to interpret tensile response are not recommended.

The elastic modulus, E_c , the tensile cracking strength, f_{cr} , and the tensile strain at localization, ϵ_{tu} , are identified in the illustration. The elastic modulus is determined according to the tangent slope of the initial elastic tensile stress-strain response. The cracking strength is defined as the stress at the intercept of a line with a slope equal to the elastic modulus and an offset of 0.02 percent. The tensile strain at localization is defined as the strain wherein the stress permanently drops below the cracking strength.

The elastic-plastic model is observed to nearly mimic the experimental result from the initiation of loading until the stress reaches γ times the tensile cracking strength. At this point, the model response sustains this tensile resistance until the strain at localization is reached.

Although most UHPC mix designs offer this type of elastic-plastic response, some UHPCs offer a tension hardening response wherein the tensile resistance increases after first cracking until the localization strain. This case is also being considered in the development of this overall guidance, with a similar but separate tensile response model to be proposed.

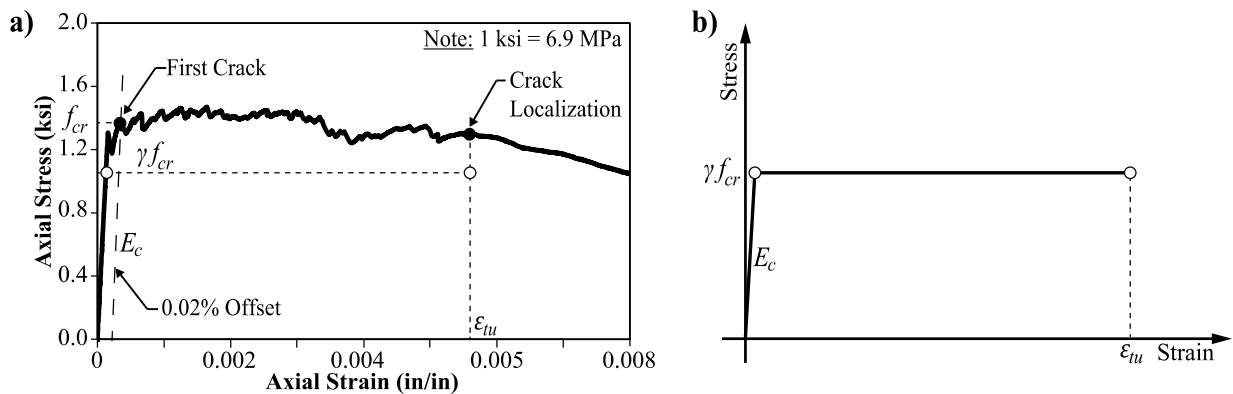


Figure 2. (a) Experimental tensile response and (b) tensile stress-strain model for UHPC

4.3. Structural Models for UHPC

Given the extra effort involved in defining and validating the full mechanical response of the UHPC, it is appropriate to use the simplified tension and compression response models when designing UHPC structural elements. Simply, these response models can be applied to critical cross-sections to determine the resistance of the element.

In flexural design, a strain compatibility approach is employed. Herein, plane sections remain plane and the UHPC compressive and discrete steel reinforcement tensile resistances are

supplemented by the UHPC tensile resistance. Figure 3a provides an illustration of the flexural analysis process for a reinforced UHPC element. Even though the tensile resistance of the UHPC might only be 1 ksi (7 MPa), the cross-sectional area in tension is sufficient to provide a non-negligible increase to the element’s flexural resistance. The idealized flexural moment-curvature response of a steel reinforced UHPC member is illustrated in Figure 3b. The UHPC flexural behavior has four key points. Point C represents the initiation of the first crack occurring when the strain in the extreme tension layer reaches the cracking limit of UHPC, $\epsilon_{cr} = f_{cr}/E_c$. Point Y indicates the yielding of the reinforcing steel occurring when the steel strain, ϵ_s , is equal to the yield strain, ϵ_y . Point L identifies the localization of the cracks, beyond which the UHPC can no longer contribute to tension capacity of the member. At this point, the strain in the extreme tension layer is equal to the localization strain, ϵ_{tu} . Point U indicates the crushing of compression UHPC, occurring when the strain in the extreme compression layer reaches the ultimate strain of UHPC, ϵ_{cu} .

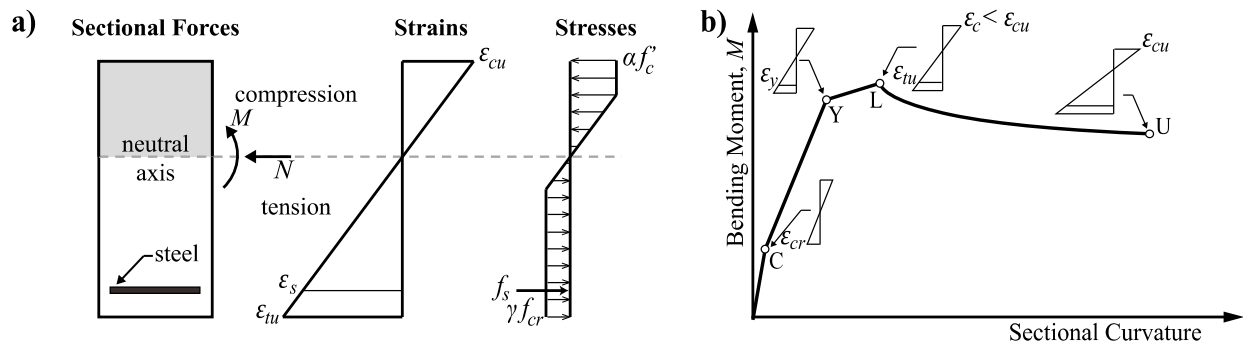


Figure 3. (a) Flexural design of a UHPC element and (b) flexural member response

In beam shear design, resistance can be determined by resolving shear into its component principle tensile and compressive components then assessing the resistance offered by the UHPC and any discrete reinforcements. For design, this process requires the prediction of the principle tensile angle. Existing methodologies for determining the shear principle compressive angle can be utilized here. Figure 4 provides an illustration showing the resistance offered by a UHPC element subjected to beam shear. Equation 2 conceptually describes the resistance offered by a UHPC element subjected to beam shear, where b_w is the web thickness, d_v is the distance between resultants of tensile and compressive forces, θ is the shear crack angle, and γ_f is a reduction factor accounting for fiber orientation and biaxial effects. As can be observed from the illustration and the equation, the application of the UHPC sustained tensile resistance to the shear cross-sectional area can provide a significant shear resistance. Thus, it may be feasible to reduce the width of the web and/or reduce the amount of steel shear reinforcement in the beam.

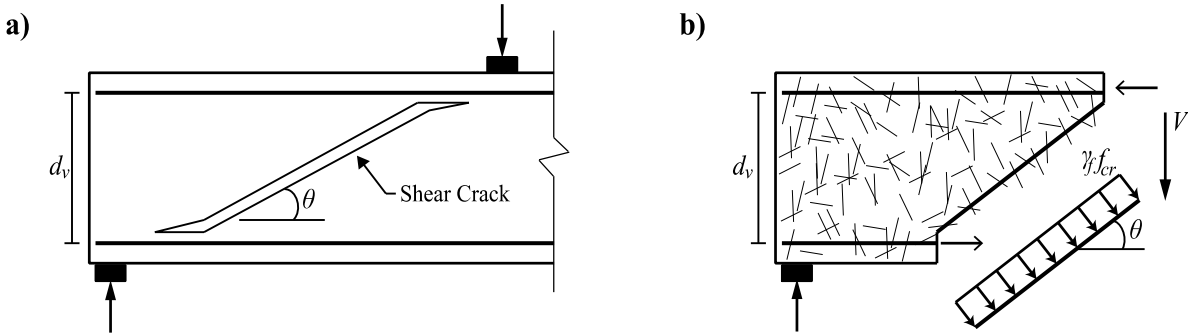


Figure 4. Beam shear design of a UHPC element

$$V_{UHPC} = \gamma_f b_w d_v f_{cr} \cot(\theta) \quad (\text{Eq. 2})$$

Other key structural design consideration cannot be easily addressed through the application of stress-strain-based concepts. For these cases, it is expected that either existing performance models will be calibrated for UHPC through the use of emerging data sets or structural testing will be completed to develop new empirical relationships. An example of the former is the case of prestress losses wherein creep and shrinkage models are being modified to better predict time-dependent UHPC behaviors. An example of the latter is the refinement of predictive relationships for the development length of reinforcing bars in UHPC.

4.4. Construction Guidance

The construction of UHPC structural elements differs from conventional concrete construction due to a few key considerations. These include the fact that 1) UHPC mix designs may be more sensitive to environmental conditions during mixing and placement, 2) UHPC mechanical properties can be affected by the placement methods employed in construction, and 3) common conventional concrete construction rules of thumb (e.g., appropriate formwork tightness, consolidation methods, finishing techniques) may not apply.

Construction guidance pertains broadly to the use of UHPC and thus some relevant guidance has already been published elsewhere. Of note, the FHWA report HRT-14-084 titled *Design and Construction of Field-Cast UHPC Connections* provides some construction guidance (2014) as does FHWA report HIF-18-030 titled *Example Construction Checklist: UHPC Connections for Prefabricated Bridge Elements* (2018). The American Concrete Institute's UHPC technical committee is also in the process of developing guidance for the materials and methods of construction with UHPC. Given the existing and emerging guidance on UHPC construction, the AASHTO guide specification will focus on key construction-related topics that are of greatest significance.

4.5. Promising Applications

As a class of materials, UHPC creates opportunities to reconsider common infrastructure solutions. The fact that UHPC is similar to conventional concrete makes it easier to adopt than some other emerging solutions. The fact that UHPC solutions can facilitate modifying construction schedules, creating heretofore improbable elements, and delivery of exceptionally robust facilities means that

owners and designers across the community of practice will be interested to learn more about the potential value of UHPC.

The most promising solution to date has been the use of UHPC for field-cast connections between prefabricated bridge elements. With nearly 300 deployments across the U.S. and Canada over the past 10 years, this solution has proved to be the entry point by which dozens of infrastructure owners have become familiar with UHPC. This breadth of engagement has begun to spawn maintenance-based solutions such as expansion joint header repairs, corroded steel beam bearing stiffener repairs, and honeycombed concrete repair. An emerging application with the potential to offer major benefits nationwide is the use of UHPC for rehabilitative overlays of concrete bridge decks.

As structural design guidance becomes more readily available, the opportunities to use UHPC for primary structural elements will become more prevalent. One promising application that is already nearing realization is the use of UHPC for precast, prestressed piles. Traditional substructure elements, particularly those in aggressive soils or water, have proven to offer substandard long-term performance. Given the difficulty in monitoring and replacing substructure elements, the engagement of the durability properties of UHPC in these elements can offer long-lasting benefits that outweigh the initially higher cost of the material.

Finally, UHPC can allow for slimmer cross-sections, longer spans, and otherwise optimized primary structural elements. These advantages can reduce structure dead load, eliminate intermediate supports, decrease seismic demand, and create aesthetically pleasing solutions. The ongoing work by El-Helou and Graybeal (2019) on the development a 300 foot (91 m) long pretensioned girder with a weight per unit length similar to an existing 200 foot (61 m) long conventional concrete girders speaks to the potential advantages of UHPC. Although such a girder would be a challenge to transport, its use on multispan water crossings with barge access could be very advantageous.

5. Conclusions

The development of structural design guidance is a key step in the maturation of UHPC technology within a community of practice. Following a first principles approach that minimizes empiricism and maximizes clarity of concept, FHWA's efforts to develop the necessary content for an AASHTO guide specification are well underway. It is anticipated that this guide specification will open avenues to broader use of UHPC in primary structural elements such that novel UHPC-based infrastructure solutions become commonplace.

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