

The First North American Broad Based Structural Design Guide on UHPC – ACI 239C

Author(s) & Affiliation: V.H.(Vic) Perry, M.A.Sc., F.C.S.C.E., F.E.I.C., F.E.C., P.E.N.G., President, V.i.Consult Inc., Paul White, P.E., P.E.N.G., Bridge Engineering Manager, LafargeHolcim and Theresa(Tess) M. Ahlborn, Ph.D., P.E., F.A.I.C., F.P.C.I., Professor, Michigan Technological University.

Abstract: ACI 239C “Structural Design of Ultra-High Performance Concrete” (UHPC) Subcommittee was formed in 2015 with the mid-term goal of developing a new structural design guide for UHPC. Under the guidelines of the American Concrete Institute (ACI) an Emerging Technology Report (ETR) on the structural design of ultra-high performance concrete is being prepared by the subcommittee ACI 239C. The subcommittee of international UHPC experts is targeting a balloted document for completion in 2018. This will be the first North American generated broad based structural design guide for UHPC. This paper covers the background and brief outline of the future structural design document and other North American code and standard developments, with an overview of the technology development and challenges facing the deployment.

Keywords: structural design, standards, UHPC, modeling, analysis, strength, durability

1. Introduction

The ACI 239 developed the following definition, pending approval: “Ultra-High Performance Concrete (UHPC) is a cementitious, concrete material that has a minimum specified compressive strength of 150 MPa with specified durability, tensile ductility and toughness requirements; fibres are generally included to achieve specified requirements” (ACI 239, 2012). UHPC is a family of products with a range of formulations that are used for different applications. These formulations vary in raw material ingredient dosages, fiber types and curing regimes. The material matrix is manufactured principally from fine materials such as sand (< 400 microns[0.002 in]), ground quartz, Portland cement and silica fume or other pozzolans. The matrix normally contains small fibres (12 mm x 0.2 mm diameter[0.5 in x 0.008 in]) in a very high dosage rate of 2% by volume (types can be high carbon steel, PVA or Glass). The matrix which contains a high cement content and a low water-cement ratio exhibits a high modulus of rupture and the high fibre loading combine to provide a high tensile property and, depending on fiber type, a strain-hardening post crack. The high compressive and tensile properties of UHPC also facilitate a high bond stress and hence, a short bond development length for rebar embedment. The use of fine materials for the matrix also provides a high aesthetic surface with the ability to closely replicate surface textures and finishes. The matrix provides a very dense material with and low permeability (Chloride ion diffusion $0.02 \times 10^{-12} \text{ m}^2/\text{s}$[$0.07 \times 10^{-12} \text{ ft}^2/\text{s}$]) to prevent the ingress of chlorides or other aggressive agents (Lafarge Website, 2013).

By utilizing the UHPC material’s unique combination of improved mechanical properties including strength, durability, ductility and workability, infrastructure construction and performance is accelerated, improved, and advanced. Benefits include: simplified construction techniques, speed of construction, improved durability, reduced maintenance, reduced out-of-service duration, reduced element size and complexity, extended serviceability life and improved resiliency.

In the overall history of concrete, UHPC is still a very young material, albeit has been researched for over 30 years, and in development for approximately 20 years. Acceptance for UHPC has been growing at a moderate pace, with recent trends showing accelerated popularity among architects and bridge engineers, mainly for its aesthetic and durability properties. UHPC research started in Europe in the 1970's and late 1980's. By the early 1990's, it was recognized as a potential new “revolutionary” material for the construction industry.

Due to the lack of North American codes and standards for UHPC, early projects were designed with conservative approaches, then, fully prototyped and load tested to failure. Before any construction started, full-scale load testing results were reviewed and any necessary design revisions could be made. In every case the load test proved the designs to be very conservative; however, the designs were not revised.

Following several years of continued testing, research, and successfully constructing demonstration projects, an acceleration of the adoption of this technology was expected. However, the lack of codes and standards created an interesting challenge and neither the owner nor designer wanted the liability of using UHPC without an applicable design standard.

2. Background

Early introduction and testing of UHPC for use in North American bridge structures and marine environments began in 1994, over 20 years ago (Perry 1, 2015). Raw material sourcing and formulating resulted in the preparation and placement of UHPC test prisms at the US Army Corps of Engineers (USACE) Long-Term Marine Exposure Station at Treat Island, Maine in 1996 (Thomas et al, 2012). Visual inspections determined that, after nearly 20 years, the prism corners are still sharp and crisp. Additionally, chloride ion penetration tests have revealed that the permeability of the UHPC samples is significantly lower (or an order of magnitude better) than High Performance Concrete (HPC) (Thomas et al, 2012).

The first use of UHPC in a North American bridge was in 1997, for construction of the Sherbrooke Pedestrian Bridge (Figure 1) in Quebec, Canada (Perry & Seibert). This 60 m[180 ft] clear span bridge was constructed from six precast 3-D Space Truss UHPC elements, and post-tensioned together on site. Although not a highway bridge, it has been exposed to light vehicle loadings for winter snow removal and severe freeze/thaw conditions as well as deicing salts for almost 20 years.



Figure 1: Sherbrooke Pedestrian Bridge, Quebec, Canada (1997)

In 2001, the US Federal Highway Administration (FHWA) initiated a research program to evaluate and introduce UHPC into the U.S. Highway program (Graybeal, 2008). From 2006 through 2014 FHWA published several documents on UHPC, including a design guide for Field Cast Connections of Precast Bridge Element. Additionally, under a FHWA funded program Iowa State University published a design guide for the design of UHPC Waffle Deck Bridges.

From 1997 to 2012, a variety of UHPC precast bridge elements were used on nine bridge superstructures in North America. In parallel to developing the bridge market for UHPC, other market applications were being advanced. In Canada, architectural applications and urban furniture were in development; while in the U.S.A. high security applications were becoming important.

As of the end of 2015, over 130 bridges with UHPC elements have been completed in North America. These include either precast bridge elements or field-cast connections (for precast bridge elements) or, in some cases, both precast and field-cast UHPC solutions. The material has also been implemented for a range of other precast architectural and structural applications, such as cladding systems, high security products, wastewater treatment troughs, urban furnishings, underground utility products, canopies, struts and columns (for a light rail transit station), plus others.

During this same period from the late 1990's, outside of North America, UHPC was also being developed in a number of regions, such as France, Australia, Japan, Germany, Korea, China and others. However, unlike North America, several other countries began the process of writing standards, codes and guides on UHPC. France introduced its first UHPC Design Guide in 2001 and a subsequent updated version in 2013, entitled “Scientific and Technical document on Ultra High Performance Fibre-Reinforced Concrete, Recommendations” (AFGC, 2013). In 2017 France will release new standard NF P18-470 “Bétons fibrés à Ultra-Haute Performances (UHPC). Australia introduced a structural design guide in 2000 and Japan in 2006 (Gowripalan & Gilbert, 2000 & Japan Society of Civil Engineers, 2006). The Swiss society of engineers and Architects have released a new guide prSIA 2052 “Bétons fibrés Ultra-Performant: Matériaux, dimensionnement et exécution (UHPC: Material, dimensioning and construction)”. While several countries did begin the process of introducing structural design guides to assist engineers with the design of structures, there still was a lack of standards for testing and specifying materials (Perry 2, 2015).

In 2012, the American Concrete Institute initiated a committee on UHPC, “ACI 239 – UHPC”, which commenced the task of collecting a group of industry experts and defining UHPC. The committee has formed several sub-committees which are now focused on two Emerging Technology Reports, including one report on the structural design of UHPC.

In 2013 a small industry group made a presentation to the American Society for Testing and Materials (ASTM) with the intention to start developing materials test standards for UHPC. Subsequently work has started within ASTM to develop a “Standard Practice for Fabricating and Testing Specimens with UHPC”.

3. The Challenges of Designing Structures with UHPC within current North American Codes & Standards

Considering the superior properties of UHPC and the potential benefits of a more resilient infrastructure, it is often believed that UHPC should be adopted more rapidly. An obvious question could be, “Why don’t more bridge engineers use UHPC in their designs?”

In 1994, when UHPC was being introduced for infrastructure projects, the engineering community was not aware of the new technology and there were no existing codes or standards that supported the use of a concrete with a compressive strength of over approximately 70 MPa(10ksi), nor did any code recognized the design properties of concrete in tension. Furthermore, a bridge engineer’s job “one” is to protect the public, and not to encourage new technologies that don’t meet the codes and standards. The bridge engineering community, by training and responsibility, is to be conservative and not take unnecessary risks. The lack of adequate structural design codes, material codes and test standards all contributed to a slow adoption rate for this new technology.

3.1. Current Testing Standards

The properties of UHPC are typically an order of magnitude superior to high performance concrete and, therefore, many of the current ASTM materials testing standards do not provide meaningful data or in many cases the test result is within testing error, thereby rendering the result useless. Currently materials engineers use adhoc modified existing ASTM and AASHTO test material standards. Consequently, there is a need to develop new testing standards that provide meaningful test results for a full range of UHPC material properties. These tests are necessary in order to categorize different UHPC’s and to provide reliable and reproducible material properties for structural engineers to use in the design of UHPC structures.

3.2 Current Materials Standards

Even though this technology uses basically the same types of raw materials and equipment as normal concrete, there are many significant differences that require a new approach to implementing the technology. These significant differences, such as the selection and proportioning of the raw materials, the batching sequence and high batching energy demands, the cost of the raw materials and the need for superior QA/QC to reduce variations can only be consistently assured by the development of a new UHPC material standard.

In North America today, there does not exist an UHPC materials code or standard that provides a clear definition nor guidance on categorizing UHPC. Any high performance concrete today can claim to be UHPC and in many cases materials are being presented as UHPC without any code or standard to prove or disprove the claim.

3.3 Current Structural Design Codes

Today there is no North American broad based structural design guideline, standard or code that provides a complete document to an engineer on designing a structure with UHPC, as currently exists for conventional concrete, structural engineers are required to use existing codes in NA or guides from other countries, then apply conservative safety factors, then load test to validate full sized elements before proceeding with the full construction. This process of testing increases initial

costs of materials, test elements, testing procedures and time delays. In many cases the use of UHPC loses to other more conventional solutions due to these added costs, even though all parties recognize the UHPC solution to be superior to the status-quo.

4. Current Activities On-going in North America on Codes and Standards for UHPC

The following provides a synopsis of on-going work in UHPC codes and standards development in North America.

4.1 ASTM

Currently under the auspices of ASTM Sub-committee C09.61”Strength”, a new “Standard Practice for Fabricating and Testing of Specimens from UHPC” is being developed to address the lack of available testing standards. The development and adoption of a new material specific and appropriate testing standard is the first step to writing any future design (material or structural) standards (ASTM, 2015). All future design standards will necessarily have to specify testing standards which will define the process to determine the material properties used in the design and construction process.. For example, today the pending UHPC definition by ACI includes a minimum specified compressive strength of 150 MPa and there is no standard test for compressive strength of UHPC. The new ASTM standard practice (Target December 2016) will provide the methods to verify if a product can be defined as a UHPC.

4.2 CSA

In December of 2015, the Canadian Standards Association (CSA) formed a new “Working Group on UHPC” under A23.1, Chapter 8, with the mandate to develop a new annex on UHPC materials (CSA A23.1, 2014). The new annex will cover everything on UHPC materials such as; categorization (See Table 1), characterization, raw materials, proportioning, production, mixing, transporting, formwork, placing, finishing and QA/QC. The working group is anticipating completing a first balloted document by the end of 2016. The document would then go to main committee for balloting and target to be published in the 2019 edition of the next CSA A23.1-19.

Table 1: Proposed UHPC Categories

Class		H	S	N
Mechanical properties		Strain Hardening Tensile Properties	Strain Softening Tensile Properties	Non-Fibre Matrices
	1	$f'_c > 120$ MPa $f'_t > 5.0$ MPa other mechanical & durability properties		
	2	$f'_c > 120$ MPa 3.0 MPa < f'_t < 5.0 MPa other mechanical & durability properties		
	3	$f'_c > 120$ MPa f'_t = not required other mechanical & durability properties	-	-

Example: Class H1 is a UHPC with a minimum characteristic design compressive strength of 120 MPa, has a minimum characteristic design tensile strength of 5 MPa and exhibits strain hardening post cracking of the matrix.

4.3 ACI

In April of 2014, at the ACI Spring 2014 Annual Meetings, ACI 239 established a new sub-committee ACI 239C “Structural Design of UHPC”, with a mandate to develop an Emerging Technology Report (ETR) on the Structural Design of UHPC. This new sub-committee, a diverse group of international industry experts, has commenced the task of writing a Terms of Reference (TOR) for the new ETR on the Structural Design of UHPC. Target completion is to have a balloted document by the end of 2018 (ACI 239C, 2015).

5. The Scope and Contents of the Proposed ACI 239C “Structural Design of UHPC”

ACI 239C is currently developing an ETR on the Structural Design of Ultra-High Performance Concrete. The ETR will provide a document that structural engineers can use to design structures with UHPC. The ETR will summarize current design methods in use and identify the gaps for future research. The ETR is anticipated to be completed within a two year timeframe and be valid for approximately 5 to 10 years, at which time the document would be withdrawn and a proposed Structural Design Guide would be revised and issued.

The following is a summary of the proposed Table of Contents for the ETR:

- 1.0 Introduction**
 - 1.1 Scope
 - 1.2 Definitions
 - 1.3 Notation and Terminology
 - 1.4 Referenced Standards
- 2.0 Mechanical Properties**
 - 2.1 Compressive Behavior
 - 2.2 Tensile Behavior
 - 2.3 Modulus of Elasticity
 - 2.4 Poisson’s Ratio
 - 2.5 Fiber-Matrix Interaction
 - 2.6 Bond-
 - 2.7 Creep Shrinkage
 - 2.8 Thermal Characteristics
 - 2.9 Durability Cyclic Strength and Stiffness Degradation
 - 2.10 Impact
- 3.0 Demand Forces and Stresses**
 - 3.1 Cross-Sectional Internal Forces and Moments
 - 3.2 Principal Stress Calculations
- 4.0 Sectional Strength Design**
 - 4.1 Compression
 - 4.2 Flexure
 - 4.3 Shear
 - 4.4 Torsion
- 5.0 Direct Strength Design**
 - 5.1 Principal Stresses
 - 5.2 Failure Criteria
- 6.0 Design for Serviceability**
 - 6.1 Deflection
 - 6.2 Vibration
 - 6.3 Shrinkage and Temperature
- 7.0 Design for Durability**
 - 7.1 Exposure Classes
 - 7.2 Crack Width Limits
 - 7.3 Life Cycle Assessment

8.0 Composite Construction

- 8.1 Steel Reinforcement
- 8.2 UHPC-Conventional Concrete Interaction
- 8.3 UHPC-Steel Composites

Appendix A: Material Characterization Methods

Appendix B: Simulation-Based Design

Appendix C: Case Studies & Examples

At this time, it is anticipated that the ETR on structural design will be restricted and only applicable to UHPC's that contain fibers. While the UHPC materials standards referenced in CSA Section 4.2 Table 1 covers a broader categorization of UHPC's, the ACI 239C ETR will be suitable with category H1, H2, S1 or S2, only.

6. Conclusions

In the overall history of concrete, UHPC is a very young material, albeit has been researched for over 30 years and in development for approximately 20 years. Acceptance has been growing at a moderate pace, with recent trends showing an accelerated popularity among architects, bridge owners and engineers, mainly for its performance, and durability properties.

Today numerous excellent examples exist showing how the technology can provide value to the owner and end-users. These projects, with up to more than 20 years of in-service data, validates the performance of the material. There exist today hundreds of completed projects worldwide that use UHPC and perform as expected. These completed projects demonstrate to the industry that the technology is working and meets the needs of the users. It also demonstrates that codes and standards are required that provide equally documented code information to all industry users in North America

Currently, structural design guides have been written in countries on every continent, except Africa and North America. In 2013, the American Concrete Institute (ACI) established committee ACI 239 UHPC. In 2015, the American Association of Testing and Materials (ASTM) begin to write standards that recognize UHPC. In 2016 the Canadian Standards Association began writing a materials standard for UHPC. All of these organizations are in the early stages of developing codes and standards for UHPC. The demand of the material is growing and precasters / contractors are learning how to work with the technology.

The application of this technology is growing and the users /specifiers are demanding a better way to ensure that the properties specified are the properties delivered in the final project. This family of concretes requires new test methods, new materials codes and new structural design codes. There is a need for standards organizations to more rapidly address the growing demand for standardized testing of new technologies.

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