Design of UHPC Structural Members: Lessons Learned and ASTM Test Requirements

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Abstract
Over the past decade, ultra-high performance concrete (UHPC) has been used in several pilot projects, which included designing of different bridge components. In each case, it became clear that the design efficiency and cost effectiveness of the UHPC structural member was not possible when the conventional approaches developed for normal concrete members were followed. More efficient structural design solutions were realized when alternative geometries and/or unique properties of the UHPC were taken advantage of in the design process. Structural testing of these members and/or field testing of bridges designed with UHPC structural members showed that their performance was extremely satisfactory in spite of adopting new design concepts and alternative geometries. Drawing design experience from bridge girders to bridge decks to UHPC piles to wind turbine towers, this paper summarized the important lessons learned and established ASTM test requirements that could facilitate designing of cost-effective UHPC members and connections with satisfactory performance. In this process, ultimate strength for flexure, shear and torsion, fatigue resistance, serviceability issues and long-term behavior of different UHPC members were given consideration.

Keywords
UHPC, design, pile, ASTM, tower, bridge, deck, HPC, concrete, testing, wind, power, precast, girder

Disciplines
Civil Engineering | Geotechnical Engineering | Structural Engineering

Comments
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Over the past decade, Ultra-High Performance Concrete (UHPC) has been used in several pilot projects, which included designing of different bridge components. In each case, it became clear that the design efficiency and cost effectiveness of the UHPC structural member was not possible when the conventional approaches developed for normal concrete members were followed. More efficient structural design solutions were realized when alternative geometries and/or unique properties of the UHPC were taken advantage of in the design process. Structural testing of these members and/or field testing of bridges designed with UHPC structural members has shown that their performance was extremely satisfactory in spite of adopting new design concepts and alternative geometries. Drawing design experience from bridge girders to bridge decks to UHPC piles to wind turbine towers, this paper summarizes the important lessons learned and establishes ASTM test requirements that can facilitate designing of cost-effective UHPC members and connections with satisfactory performance. In this process, ultimate strength for flexure, shear and torsion, fatigue resistance, serviceability issues and long-term behavior of different UHPC members are given consideration.

Keywords

UHPC; design; pile; ASTM; tower; bridge; deck; HPC; concrete; testing; wind; power; precast; tower; girder

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Introduction

Ultra-High Performance Concrete (UHPC), referenced throughout this paper including all referenced applications, is a Reactive Powder Concrete (RPC) mixture combined with high strength steel fibers. Typical composition of the UHPC mixture used for applications presented in this paper is given in Table 1 in terms of weight per unit volume, mass ratio relative to cement, and volume fraction. The quantity of superplasticizer, a high-range water-reducing admixture, expressed in this table is the weight of the solid fraction while the liquid fraction is included in the weight of the water. Use of densely packed filler materials, such as silica fume, combined with small particle sizes that are typically kept below 0.6 mm creates a homogeneous, nearly impermeable UHPC matrix with more uniformly dispersed cement grains.

Table 1: Typical components in a UHPC mixture [1,2]

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight /m³ (kg)</th>
<th>Mass ratio/cement</th>
<th>Volume fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>92.1</td>
<td>1.43</td>
<td>38.8%</td>
</tr>
<tr>
<td>Cement</td>
<td>62.9</td>
<td>1.00</td>
<td>22.7%</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>20.8</td>
<td>0.33</td>
<td>10.6%</td>
</tr>
<tr>
<td>Crushed Quartz</td>
<td>19.3</td>
<td>0.30</td>
<td>8.1%</td>
</tr>
<tr>
<td>Fibers</td>
<td>14.0</td>
<td>0.22</td>
<td>2.0%</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>1.3</td>
<td>0.02</td>
<td>1.4%</td>
</tr>
<tr>
<td>Water</td>
<td>14.7</td>
<td>0.23</td>
<td>16.5%</td>
</tr>
</tbody>
</table>

UHPC has significant advantages over normal concrete and high performance concrete (HPC) in both strength and durability; compressive strength of normal concrete is typically less than 50 MPa whereas the corresponding value for HPC is in the range of 50 to 100 MPa. With the compressive strength as high as 180 MPa, capillary porosity as low as 1.5 percent and absence of interconnected pores that permit migration of water and chlorides, UHPC is ideally suited for bridge applications even in harsh environments. The lack of interconnected pores was observed by the author in a microscopic evaluation, which is a feature of this class of concrete due to interconnected pores being blocked during hydration cement [3]. The enhanced durability properties have primarily motivated the use of UHPC in bridge applications in the U.S., starting with several of them in the state of Iowa—a state with one of the highest number of structurally deficient bridges [4]. The unique properties of UHPC have also promoted the use of UHPC in field applications specifically for establishing connections between precast members made from normal concrete, HPC or UHPC. Besides the durability benefits, a main advantage of UHPC connections is that they enable development of high bond strength due to its high compressive strength, allowing steel reinforcement to be anchored over a relatively short anchorage length and reduction in clear cover and spacing between reinforcing steel.

The cost of UHPC is relatively high compared to normal concrete and high performance concrete (HPC). Energy demand for producing one cubic meter of UHPC has also been cited to be twice that needed for producing one-cubic meter of normal concrete due to the use of the high amount of cement in UHPC [5]. The increased emphasis in constructing sustainable structures also suggests any negative impact to the environment due to the use of
UHPC should be given consideration. Therefore, the application of UHPC for structural design must optimize the use of the material and even perhaps limit their use to members that are more susceptible to structural and/or environmental damage. The enhanced properties of UHPC combined with innovative design concepts can result in the UHPC members requiring less than 50% material of the equivalent normal concrete members, which in turn would allow a designer to utilize UHPC and produce a sustainable structural design with reduced impact to the environment. This was successfully demonstrated by Schmidt and Teichmann in the Gaertnerplatz bridge project in Kassel, Germany [6]. By exploring suitable solutions for the 136-m long Gaertnerplatz pedestrian bridge, Schmidt and Teichmann demonstrated that the environmental impact of the UHPC solution would be less than that of normal concrete [6]. This was possible because of the use of low amounts of material in the UHPC design in comparison to conventional concrete designs, resulting in total weight of the UHPC bridge being more than 50% less than that for the normal concrete solution.

Standardizing the tests, and thereby establishing UHPC properties, are expected to minimize variations in the material properties and help establish appropriate design models for finding characteristics of members such as flexural strength, flexural cracking potential and ductility. Therefore, in order to establish the needed ASTM testing standards for key UHPC design parameters, its properties are first presented, followed by different examples of applications emphasizing what aspects largely influenced their final design and construction. Based on these controlling design aspects, ASTM test requirements are suggested.

Properties of UHPC

Characteristic engineering properties of the UHPC mixture that has been used for research at Iowa State University (ISU) as well as in most of the applications in the U.S. are summarized in Table 2; the test setups used to establish the properties are shown in Figure 1. Compared to what is typically observed for normal concrete and HPC, variation in the reported UHPC properties is typically minimal provided sample preparation is done carefully. Furthermore, as can be seen in this table, UHPC possesses many beneficial engineering properties over normal concrete and HPC. Although the UHPC has tensile strength as much as over four times the tensile strength of normal concrete and possesses some dependable inelastic tensile behavior, the tensile strength of UHPC is only a fraction of its compression strength, suggesting that these characteristics are still not conducive to develop optimal design solutions. However, this challenge can be easily overcome by utilizing a high amount of prestress, which is possible due to the high compressive strength of UHPC that is as high as five times the compressive strength of normal concrete. Since UHPC leads to thin members with reduced cross-sectional areas, inducing high amounts of prestress can be achieved effectively without needing an excessive amount of prestressing steel.

While it is not a critical requirement, thermal curing is ideal for UHPC, which requires subjecting UHPC members to 194°F over 48 hrs. This curing process can be achieved in a precast concrete plant and was used in all applications summarized in this paper when UHPC members were prefabricated. Most of the 450 x 10⁶ shrinkage strain reported in Table 1 occurs during thermal curing of the UHPC members. After curing, the UHPC members are expected to undergo almost no further shrinkage.

As outlined in the introductory paragraphs, the enhanced durability properties of UHPC when compared with those of normal concrete and HPC (see Table 3) are important driving factors for the application of UHPC. The durability characteristics of UHPC, particularly its excellent resistance to chloride ion penetration due to its low capillary porosity, make it extremely resistant to corrosion, even with the inclusion of a large proportion of steel
fibers in the UHPC mixture. Table 4 lists the comparable properties for normal concrete and HPC to emphasize the significant durability qualities of UHPC.

### Table 2: Typical material properties of normal concrete, HPC and UHPC [1,2,7]

<table>
<thead>
<tr>
<th>Property</th>
<th>Normal Concrete</th>
<th>HPC</th>
<th>UHPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength</td>
<td>28-50 MPa</td>
<td>50-100 MPa</td>
<td>180 MPa</td>
</tr>
<tr>
<td>Elastic Tensile Strength</td>
<td>3.2 – 4.5 MPa</td>
<td>4.0-5.6 MPa</td>
<td>9.0 MPa</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td>3.2 – 4.5 MPa</td>
<td>4.0-5.6 MPa</td>
<td>11.7 MPa</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>24 – 33 GPa</td>
<td>30-40 GPa</td>
<td>51 GPa</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>400 - 800 x 10^{-6}</td>
<td>400 - 800 x 10^{-6}</td>
<td>450 x 10^{-6}**</td>
</tr>
<tr>
<td>Creep coefficient</td>
<td>≥ 2.0</td>
<td>0.5 – 1.0</td>
<td>0.78</td>
</tr>
</tbody>
</table>

*Assumed based on reported results

### Table 3: Typical durability properties of normal concrete, HPC, and UHPC [2]

<table>
<thead>
<tr>
<th>Property</th>
<th>Normal Concrete</th>
<th>HPC</th>
<th>UHPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capillary Porosity</td>
<td>8.3 %</td>
<td>5.2 %</td>
<td>1.5 %</td>
</tr>
<tr>
<td>Water Absorption Factor</td>
<td>60</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Chloride Ion Penetration Depth</td>
<td>23.0 mm</td>
<td>7.5 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Carbonation Depth</td>
<td>28 in.</td>
<td>NA</td>
<td>2.5 – 5.0 mm</td>
</tr>
</tbody>
</table>

### Applications

This section presents examples of UHPC applications for several bridge components (i.e., girders, decks and a precast pile), seismic columns, and wind turbine towers. For each of these applications controlling design criteria are discussed such that the needed ASTM requirements for UHPC can be formulated. As noted previously, bridge applications and seismic columns were primarily motivated by UHPC’s enhanced durability properties, while applications to wind turbine towers benefitted from excellent engineering properties. In each of the applications, UHPC was used to produce the selected structural member in its entirety. In these designs, the member depth, member thickness, clear cover to reinforcing steel and spacing between reinforcing steel were reduced to increase the efficiency of the sections. Besides the application to structural members, UHPC has also been used to develop structural connections—the most popular application of UHPC in the U.S. today. The quantity of UHPC is minimized when used only in connections, where the strong connection-weak member concept is typically adopted, meaning that under extreme load circumstances, the failure would develop in the members and not in the connections joining the structural members. This section therefore ends with two examples of UHPC connections in bridges.

**Bridge Girders**

Through collaboration among Iowa Department of Transportation (DOT), ISU, Federal Highway Administration, and Iowa Highway Research Board (IHRB), the State of Iowa has led implementation of two types of bridge girders. The design of the UHPC girder, which led to the first UHPC bridge in the U.S. in Wapello County, Iowa, was
approached conservatively, yet keeping the overall cost of the bridge to a minimum. As shown in Figure 2, this bridge girder used a slightly modified standard Iowa DOT section, but with an increased amount of prestressing, ultimately increasing the girder span [8]. The original bulb tee C-beam is 1.14 m deep and uses 22, 15.2-mm strands to span 24.6 m. The UHPC girder was 1.07 m deep and designed with 49 strands to span 33.8 m. Consequently one area of cost saving resulted from the increased girder span that allowed replacement of the original two-span bridge with a single span bridge, thereby eliminating the need to construct an intermediate pier and its foundation. The combination of significantly higher prestressing than in a comparable normal concrete girder and relatively high tensile strength of UHPC also help eliminate the transverse reinforcement in the girder. A 21.4-m long girder with the cross section at full-scale was subjected to flexure and shear tests (see Figure 2). While the tests confirmed that the girder had adequate shear and flexural resistance, it was realized that the approach used for shear design was overly conservative and a refined shear strength calculation could be achieved by defining the shear strength preferably as a function of width of the shear crack up to an acceptable limit. One complicated matter in this regard is that extensive microcracking and subsequent localized shear crack would typically develop (see Figure 3). Therefore, the sequence and extent of formation of the two crack types should be accounted for in establishing the permissible shear strength.

Following the design and full-scale testing of two generations of Pi-girders for bridge application by FHWA’s Turner-Fairbank Laboratory and the Massachusetts Institute of Technology (MIT), this uniquely-shaped girder from the second generation, was first implemented at a bridge site in Iowa [9,10]. A full-scale unit of the UHPC Pi-girder used at this bridge site can be seen in Figure 4. In comparison to the traditional I-shape as used for the girder in Figure 2, this new shape brings new challenges due to the integrated deck, thin web and flange sections, and increased span length. A concern raised during the design was the effectiveness of the steel diaphragm used for improving load distribution among Pi-girders [10]. However, the overall behavior of the girder from the field tests confirmed that its span length can be increased, and that live load distribution factors can be reduced so that the pi-girders can be used more optimally than in this particular project.

As with other normal concrete and HPC girders, the design of both girder types described above should satisfy the flexure and shear design, along with deflection and fatigue criteria. The engineering properties and other parameters needed to complete these design calculations should be reliably defined for UHPC, which include the characteristic compressive strength, flexural cracking strength, ultimate tensile strength, strength reduction factor, elastic modulus, and all variables needed to estimate the prestress loss accurately, including the creep coefficient and shrinkage strain. When new members as shown in Figure 2 and Figure 4 are developed, they are normally load tested prior to implementing them in the field. With such structural testing, scale models are frequently used to minimize the cost of the experimental program. While UHPC testing reported herein were based on full-scale, use of scale-models will be inevitable in the future. Therefore, appropriate recommendations for performing structural testing using scale models should be established. In this regard, specifying the minimum acceptable scale, providing guidance on how to deal with fiber length in scale models, and understanding the scale effects on structural behavior would be necessary.

**Bridge Decks**

The main advantage of using UHPC in bridge decks is that it prevents early deterioration of deck resulting from cracking that allows penetration of chloride especially during wintry months. Use of UHPC successfully in the entire
bridge deck was accomplished by developing a full-depth precast UHPC waffle deck system as part of the Highways for LIFE program of the Federal Highway Administration (FHWA) [11,12]. The constructability of this system with conventional mild steel reinforcement as well as structural performance of its critical connections and panels were investigated using full-scale laboratory tests, which confirmed the excellent performance of the new deck system under service, fatigue, ultimate and punching shear loads.

Following the satisfactory laboratory tests, this system was deployed on a two-lane, single-span replacement bridge in Wapello County, Iowa. This bridge, which is 10.1-m wide and 18.3-m long, was designed with five standard Iowa “B” girders, at a center-to-center distance of 2.2 m (see Figure 5) with connection details depicted in Figure 6.

To make the UHPC waffle deck panels fully composite with the girders, three types of connections were used, namely: 1) a pocket connection; 2) a longitudinal connection, and 3) a transverse connection. The pocket connection consisted of at least one shear hook extending from the top of the girder into a pocket in the waffle deck panel, which was filled with in-situ UHPC (see Figure 6a). This detail established the connection between the waffle panel and exterior or intermediate girders (see detail B in Figure 5). The longitudinal connection was used between the waffle panels and center girders. Dowel bars extending from the panels with shear hooks from the girders (as with detail B), and additional longitudinal mild steel reinforcement was used with in-situ UHPC (see Figure 6b) for this connection. The transverse connection joined two adjacent UHPC waffle deck panels utilizing dowel bars extending from the panels, placement of two additional transverse reinforcing bars, and in-situ UHPC (see Figure 6c).

To reduce the UHPC volume and the cost of the deck, a recent effort has investigated the use of UHPC as an overlay on normal concrete decks with an intention of using this technology in existing and new bridge deck. This effort involved slant shear and flexural test with varying interface roughness as shown in Figure 7. It was also assumed that the interface between normal concrete and UHPC should not utilize any mechanical elements as this would add further material and labor costs. This concept has proven to be successful when the interface between the normal concrete and UHPC layer consisted of sufficient roughness. Normal concrete deck having a broom finish surface and 3-mm or greater thick rough surface created by form liners were found to be adequate to produce satisfactory normal concrete-UHPC composite decks [13].

Beside designing these decks to satisfy flexure and shear requirements, experience from these projects reveal design values and methods for adequately characterizing fatigue behavior should be established for members designed with UHPC. As with the normal concrete structures, the fatigue characteristics can be defined using S-N curves, where S and N correspond to alternating stress and number of load cycles to failure, respectively. The mean stress will also play a part in the fatigue resistance of the UHPC member. Other equally important design calculations include selecting the interface roughness, punching shear, and anchorage and splicing of reinforcement within connections made from insitu UHPC. Given the potential for using UHPC deck without any wearing surface made from concrete or asphalt overlay as done in the Wapello county project, an appropriate procedure for ensuring a quality riding surface must be established.
**Bridge Piles**

With an objective of increasing the durability of the foundation, a tapered, H-shaped, precast, prestressed UHPC pile was developed at ISU as a means for increasing the longevity of bridge foundations [2,14,15]. The cross-section details of this pile and a frequently, used steel H-pile—used as a reference pile in this project—are compared in Figure 8. Vertical full-scale and lateral load tests on “UHPC piles in the laboratory and field revealed several benefits of the UHPC pile including significantly reduced risk of damage during driving, drivability with a greater range of hammers and strokes, and the possibility of using existing equipment for pile handling and driving.” Field testing of the UHPC piles was conducted following the ASTM Standards D1143 – 07 and ASTM D3966 – 07 [16,17], and there weren’t any concerns with following the testing procedures or characterizing the test results [14,15]. Hence, UHPC piles can be installed and field tested as the steel H-piles (see an example in Figure 9). To increase the application of this pile in the field, a welded splice connection that can be referred to as a “dry connection” was developed. Steel attachments used at the ends of UHPC piles requiring welding between two H-shaped steel plates facilitate the splicing of piles. Satisfactory performance of the splice detail has been confirmed in the laboratory and field. Anchoring of UHPC piles into precast and cast-in-place concrete blocks representing pile caps and abutments has also been successfully established in an ongoing research project.

Field experience has shown that UHPC piles can be driven in stiff soil without using any cushion on top of the pile [2,14,15]. However in order to accurately estimate the driving stresses and ensure no damage to the piles under different foundation soil conditions, accurate estimate of the tensile cracking strength, transfer of prestress, and wave velocity within the pile length are required.

**Seismic Columns**

To explore the use of UHPC in seismic regions for both bridges and buildings, three UHPC columns were designed and subjected to cyclic lateral load at ISU [18]. Under compression loading, the UHPC reaches its ultimate strength almost in a linear fashion. The strain capacity corresponding to the ultimate compression strength is about 0.0032, which is only about 10% to 15% of the strain capacity of confined normal concrete that forms the basis for ductile seismic design adopted in current practice. Development of large compressive strains within normal concrete occurs in a nonlinear fashion, which is typically limited to the column ends known as the plastic hinge zones. With mild steel reinforcement in these regions also experiencing highly nonlinear strains, the formation of dependable plastic hinge zones enables the columns to undergo large lateral displacements, experience little or no reduction in the lateral force resistance, and dissipate a significant portion of seismic energy imparted to the structure through hysteretic action.

The UHPC columns cannot be designed in the same manner as the normal concrete for seismic applications due to its limited compression strain capacity and high bond stress resulting from the ultra high compression strength. If mild steel reinforcement is used at the member end to connect the column to the foundation, the reinforcement will be fully anchored over a short distance, causing strain concentration and premature fracture of the reinforcement. Even if this concern were overcome by deboning a portion of the reinforcement, the limited compression strain capacity would still pose a challenge. As shown in Figure 10, UHPC samples with 2% steel fibers were examined under an electron microscope after they failed under uni-axial compression tests. A few of the 0.15 mm diameter, 12 mm long steel fibers were found to have experienced necking and fracture. However, most of the steel fibers experienced pull out failure as they were not designed to act as confinement reinforcement. An
attempt to increase the compression strain capacity with external confinement revealed that confinement would increase the strength of UHPC and a strength gain as much as a factor of two is possible with a high confinement. However, the corresponding stress-strain behavior remains elastic, increasing the strain capacity linearly by the same factor. This finding may be less obvious as UHPC flexural members are generally cited to produce large lateral deformations at the ultimate limit state (see an example in Figure 2). These large deformations can be attributed to small neutral axis depths resulting from high compression strength of UHPC and the corresponding increase in curvature. While the increase in compressive strain capacity and curvature can potentially increase the lateral displacement capacity of the structural member, this increase in displacement capacity combined with limited hysteretic energy dissipation capability falls well below the target values used in current seismic bridge design practice. Hence, an alternate concept was investigated for designing seismic columns.

The completed seismic column tests utilized an interface material between the UHPC column and the foundation, and unbonded post-tensioning as the tension reinforcement. In addition to ensuring full contact between the column end and foundation, the interface material was to accommodate some of the deformation under compression. The combination of the use of this interface material and unbonded post-tensioning allows the column to achieve large lateral displacements through concentrating column rotation at the column-to-foundation interface. To help dissipate the seismic energy, use of external sacrificial elements attached to the column and foundation was investigated. As shown in Figure 11 and demonstrated as part of the laboratory testing, steel angles welded to a steel foundation plate and embedded plate anchored to the UHPC column using shear studs could be used as an energy dissipating element. For the interface, the following three material options were explored: hydrostone, steel fiber reinforced grout and a pre-made glass fiber epoxy pad. Hydrostone was used to demonstrate the negative impact of not having fibers in the interface material and thus performed poorly by progressive crushing under compression. The performance of other two-interface materials was very satisfactory although the glass fiber epoxy pad showed no distress due to its high compressibility.

While all test objectives were achieved with the steel fiber reinforced grout interface and the epoxy pad, the study also concluded that a hollow UHPC column would be more cost effective than a solid UHPC column. Hence, the ability to design hollow seismic columns will require guidance on the minimum wall thickness and the possibility of including compression and shear strength characterization as a function of member thickness as member thickness may influence the fiber orientation.

**Wind Turbine Towers**

Another recent application of UHPC is in the area of designing tall wind turbine towers [19,20]. The wind energy industry has extensively used steel tubular towers over the past several years for supporting utility scale wind turbines. The commonly used hub height today is 80 m as this height facilitates the steel tower to be transported in three segments. Although within the transportation limits, the transportation of the steel tower is a time consuming and costly task that has caused transportation challenges periodically. Given that at higher elevations, faster, more sustainable wind exists that will allow an increase in both wind energy production and harvesting times, the wind energy industry has begun exploring the design of towers with hub heights of 100 m and above. Increasing the steel towers to new heights is neither straightforward nor cost effective due to the transportation allowances of the highway system. The base dimension of the taller steel tower would require transporting of the bottom segment in multiple pieces and assembling them on site. To overcome this challenge, a new tower concept
using UHPC as a construction material has been developed that allows a taller wind turbine tower to be designed and constructed without being constrained by the current transportation system.

The new tower concept—termed Hexcrete—comprised of six exterior post-tensioned columns along with panels that span the distance between two adjacent columns [20]. The panels are primarily used as bracing elements between columns so that all six columns act as a composite system to resist the loads at the operational and extreme limit states. Both the columns and panels extend the entire height of the turbine and are segmented into sizes that allow for easy transportation. Once on site, the pieces may be erected using two possible construction sequences. The first consists of connecting the columns and panels together in multiple segments on the ground similar to the ones shown in Figure 12. These segments would then be stacked and fastened together by running vertical post-tensioning through the columns (Figure 12a). At higher elevations, the number of strands required to provide the tower with sufficient load capacity is reduced. For this reason, two of the radial ducts within each column, shown in Figure 2, will be terminated at 33.5 m and 67.0 m in a 100-m tall Hexcrete tower. The center duct will extend from the foundation to the top of the tower. The second construction sequence requires each of the columns be erected to the first post-tensioning cut-off elevation. The columns are then secured by stressing each tendon, after which the panels are placed and connected as shown in Figure 12c.

To ensure satisfactory assembly of the tower, and that the entire tower would act as a composite system, three different connection details have been developed and tested under expected operational and extreme loads. All three connections produced extremely good responses in terms of transferring connection forces and meeting the force demands at the operational and extreme limit states. As for the design of the tower, UHPC was suggested for the columns, panels, joints, or combination thereof with the different material choices providing different benefits. When UHPC is not used, the corresponding member is produced using HPC or high strength concrete that focuses only on increasing the material compressive strength.

The design of the wind turbine tower, connections and observed performance of tower components reveal that appropriate ASTM requirements should be established so that use of UHPC in the wind turbine tower design can be successfully adopted. As with previous examples, the design for flexure, shear and torsion should be adequately completed for the composite tower with acceptable stresses for all structural components. There are several benefits in using UHPC for the panels, which will result in thin (i.e., thickness of 60 to 75 mm) panels. Hence understanding the panel behavior under in-plane and out-of-plane loading would be important. Furthermore, special attention should be given when establishing the working mean stress of different design actions as wind turbine towers are subjected to a significantly higher number of load cycles than bridge components. A connection that utilized in-situ UHPC relies on anchoring of reinforcing bars with a short embedment length; hence, this topic would also require guidance in terms of selecting the embedment length for a given size of mild steel reinforcement.
Connections

With the introduction of the mixing UHPC in the field, use of this material in bridge connections has been growing at a rapid pace. As detailed in Figure 6, the width of these connections is relatively small because the connections rely on anchoring the connection reinforcing bars within a short distance. In addition, the length of the connection could be reduced if, for example, the connection is between a girder and bridge deck where the connection reinforcement is extended into a pocket in the deck. Figure 13 shows two example applications. The first example used UHPC connection between UHPC precast waffle deck panels and prestressed concrete girders, and used all three types of connections shown in Figure 6, including the pocket connection. The second example is from New York where full depth precast concrete panels were connected using UHPC.

ASTM Test Requirements

In consideration of the UHPC example projects presented in this paper, Table 4 summarizes critical design actions, the primary calculations that may likely govern the design, and the corresponding design parameters. For example, when flexure is concerned, it requires estimation of flexural stiffness and strength, which in turn needs sufficient information on the compressive strength preferably with stress-strain behavior, elastic modulus, flexural cracking strength, and strength reduction factor. While information such as the strength reduction factor needs to be provided by design codes, ASTM test standards should be established for material characterization, including the testing procedures. This information is further presented in Table 5 with two specific issues: 1) consistency on the design values that have been recommended by different researchers and existing design documents; and 2) variables that need to be integrated when establishing the ASTM test standards for that specific design parameter.

While the focus of ASTM test requirements here is on the engineering properties, it is reminded that the primary motivation for using UHPC in structural applications has frequently been to increase the longevity and reduce the maintenance costs of the structures. Therefore, it is equally important to establish appropriate ASTM test requirements for key UHPC durability properties summarized in Table 3. The development of newer design mixtures for UHPC are on the rise and are generally motivated by reducing the material costs. While this effort should be encouraged, there is a tendency to focus on producing mixtures with ultrahigh strength without considering adequate evaluation on the durability properties. These new composition of materials may have unique applications; however, a clear distinction between UHPC and Ultrahigh Strength Concrete should be established when developing a standard for the material itself.

<table>
<thead>
<tr>
<th>Design action</th>
<th>Calculation likely to govern design</th>
<th>Needed design parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexure</td>
<td>Strength; stiffness</td>
<td>Compressive strength; flexural cracking strength; stress-strain response under compression and tension; elastic modulus; strength reduction factor; anchorage</td>
</tr>
<tr>
<td>Design parameter</td>
<td>Variability observed in design recommendations</td>
<td>Parameters needing emphasis within ASTM Standards</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>Not significant for a given mixture</td>
<td>Type of curing; preparation of test samples and their minimum dimensions; test setup including the test orientation with respect to the direction of casting; procedure for defining the elastic modulus and compressive strength.</td>
</tr>
<tr>
<td>Stress-strain response under compression</td>
<td>Some variations noted in the post-elastic range</td>
<td>Preparation of samples and measurement techniques for characterizing the stress-strain response including the post-peak response.</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>Not significant for a given sample type</td>
<td>Type of curing process; preparation of test samples including the shape of the section and minimum dimensions; test setup including the test orientation with respect to the direction of casting; definition for tensile strength.</td>
</tr>
<tr>
<td>Stress-strain response under tension</td>
<td>Noticeable changes in the post-peak range.</td>
<td>Preparation of samples, shape of sample and measurement techniques.</td>
</tr>
<tr>
<td>Shear strength</td>
<td>Existing recommendations have been found to be conservative</td>
<td>Shear resistance of UHPC with varying amounts of fiber quantities; influence of micro cracking on shear strength.</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Sufficient information is not currently available</td>
<td>Compressive working stress (typically much higher than those used for NC); influence of micro cracking; alternative stress with respect to mean stress.</td>
</tr>
<tr>
<td>Creep</td>
<td>Not significant</td>
<td>Curing condition; initial stress; age at...</td>
</tr>
</tbody>
</table>

‘to be defined by design codes

Table 5: Design parameters needing ASTM standards
Conclusions and Recommendations

The use of UHPC has been continuously increased in the U.S. and other countries around the world. Summarized in this paper are several applications of UHPC in structural members, ranging from bridge girders to bridge decks to foundation piles to wind turbine towers, and connections. From the design of these structural members and connections, the important lessons are: 1) structural solutions developed for normal concrete may not be directly applicable for developing cost-effective UHPC members; 2) unique properties of UHPC provide opportunities to develop innovative structural solutions with reduced member depth and thickness; 3) UHPC enables simple and reliable connections with short bar embedment lengths, and 4) to increase the wider use of UHPC, the design should make use of the unique properties of UHPC and limit its use to members and connections where this material with enhanced properties is most appropriate.

To take advantage of UHPC material in design, ASTM test requirements and standards need to be developed for several design parameters so that consistent, reliable, and cost-effective design solutions can be achieved when UHPC is chosen as the construction material. These standards may be developed for defining characteristic compression strength, characteristic tensile strength, elastic modulus, constitutive relations for both compression and tension, shear strength with respect to the width of the localized crack and/or accumulated width of the microcracks, fatigue resistance, creep coefficient, shrinkage, and thermal coefficient of expansion. In this process, the following key issues should be given consideration.

- Higher material strength: some of the testing procedures developed for normal concrete and HPC may not be applicable for UHPC and there may be a need to use test equipment with new capabilities and increased load capacities;

- Size and shape of the test samples: the test results may be influenced by the size and shape of the sample as it may affect the fiber orientation;

- Scale factor: Performance of large structural components may be established using large-scale test units but not using full-scale units. It is unclear how the dimensions and quantity of fibers should be designed in those test units.

<table>
<thead>
<tr>
<th>Property</th>
<th>Information Available</th>
<th>Curing Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrinkage</td>
<td>Not significant</td>
<td>Curing type</td>
</tr>
<tr>
<td>Thermal expansion of coefficient</td>
<td>Sufficient information is not currently available</td>
<td>Curing type</td>
</tr>
<tr>
<td>Abrasion resistance</td>
<td>Sufficient information is not currently available</td>
<td>Testing procedure, sample preparation, evaluation with consideration to surface roughness</td>
</tr>
<tr>
<td>Bond characteristics</td>
<td>Limited information is available</td>
<td>Testing procedure; test setup; reinforcement type</td>
</tr>
</tbody>
</table>
• Curing process: as with normal concrete, UHPC can be cured over 28 days. Alternatively, it can be rapidly cured over a short duration through a heat treatment that results in development of full materials strength at the end of the heat treatment process.

It is anticipated that design codes should make use of the material characteristics to be established by the ASTM standards and propose appropriate models so that design calculations for UHPC members (e.g., ultimate flexural strength and fatigue resistance) can be obtained reliably and consistently.

Acknowledgements

The author wishes to thank several organizations and individuals, who made the various UHPC research projects reported in this paper possible over the years. In particular, the authors acknowledges the financial or in-kind contributions and/or advice obtained from Benjamin Graybeal and Julie Zirlin of FHWA, Ahmad Abu-Hawash Dean Bierwagen, Kenneth Dunker and Michael Nop with the Iowa DOT, Brian Moore with Wapello County, Iowa, Todd Culp and John Heimann with Coreslab Structures (Omaha) Inc., and Vic Perry and Kyle Nachuk with Lafarge. A special thanks is also due to the following faculty members, researchers, technical staff and students who assisted or participated in the different projects at ISU: Sriram Aaleti, Muhannad Suleiman, Terry Wipf, Brent Phares, Matt Rouse, Doug Wood, Owen Steffens, Michael Shimkus, Bradley Petersen, Brian Degan, Brant Bristow, Tom Vander Vroot, Kam Ng, Jessica Heine Grant Schmitz, Rakesh Murthy, Ebadollah Honarvar-Gheitanbaf, and Pavel Beresnev.

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<table>
<thead>
<tr>
<th>Property</th>
<th>HP 250 x 85</th>
<th>UHPC pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Area (cm²)</td>
<td>108</td>
<td>366</td>
</tr>
<tr>
<td>Weight (kg/m)</td>
<td>85.1</td>
<td>90.9</td>
</tr>
<tr>
<td>Moment of Inertia (mm⁴)</td>
<td>1.22 x 10⁸</td>
<td>3.31 x 10⁸</td>
</tr>
<tr>
<td>Stiffness (E I) (N.mm²)</td>
<td>2.25 x 10¹³</td>
<td>1.83 x 10¹³</td>
</tr>
</tbody>
</table>

(a) Cross section detail (1in. = 25.4 mm)
(b) Steel vs. UHPC pile properties
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