An Evaluation of the Placement and Fiber Orientation Factors based on Existing UHPC Codes and Standards

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Abstract

In various infrastructure applications, ultra-high-performance concrete (UHPC) has been investigated widely for its exceptional structural and durability qualities. Although UHPC structures have proved structural stability at the structural level, fiber dispersion and fiber orientation due to casting procedure and construction processes remain a concern. Fiber orientation and structural performance of UHPC members are strongly influenced by the casting flow direction of freshly mixed UHPC, formwork geometry, rebar arrangement, casting device, and rheology of the mixtures. Different professional organizations across various countries have released UHPC design codes and guidelines, and each addressed fiber orientation in a distinctive way. A brief review of the influence of various factors on fiber orientation in structural elements is presented in this article. A review of existing structural design guidelines for UHPC and steel fiber-reinforced concrete materials was conducted. The method used to account for fiber orientation and dispersion was discussed. The effect of undesirable fiber orientation was compensated by different design reduction factors introduced by several design codes. Additionally, this paper discusses the underlying rationale for these design factors. The paper concludes by making recommendations to design professionals and suggesting future research directions.

Keywords: UHPC, design codes and standards, Fiber orientation, Fiber dispersion, UHPC Casting and placement methods.

1. Introduction

The orientation of fibers in ultra-high performance concrete (UHPC) refers to the arrangement and direction of fibers within the concrete matrix. The fibers can be aligned parallel or perpendicular to the direction of applied stress, or randomly distributed throughout the concrete. The orientation of fibers can be influenced by several factors, such as the mixing process, casting method, and compaction technique. The proper orientation of fibers can improve the mechanical properties of UHPC, including the compressive, tensile, and flexural strength, as well as the fracture toughness and ductility of the material.

Ultra-high-performance concrete (UHPC) is an innovative construction material that exhibits exceptional mechanical, durability, and aesthetic properties, making it an ideal material for complex and demanding structures. However, UHPC requires careful placement and quality control to ensure its performance meets the intended design criteria. Therefore, evaluating the placement and fiber orientation factors in UHPC is essential to guarantee the desired performance and durability of UHPC structures.

This article aims to evaluate the placement and fiber orientation factors in UHPC based on existing codes and standards. Specifically, this article will examine the effect of UHPC placement method, casting procedure, and casting device on the fiber orientation factor in performance-based design in existing UHPC codes. The findings of this study will help improve the reliability and applicability of UHPC in various construction applications.

The article discusses the impact of three main factors on the performance of ultra-high performance concrete (UHPC). These factors include the method used for placing UHPC, the procedure used for casting, and the device used for casting which have a significant effect on fiber orientation and dispersion that greatly influence the mechanical performance of UHPC structures. The article highlights the importance of these factors and how they affect the final quality and performance of UHPC. Additionally, the article includes a critical discussion on the fiber orientation factor in performance-based design as outlined in existing UHPC codes. The fiber orientation factor refers to the alignment and orientation of fibers within the UHPC matrix, which has a significant influence on the strength and durability of UHPC structures. The article provides insights into the impact of these factors on UHPC performance and offers recommendations for optimizing UHPC design and construction based on the latest research findings. The article highlights the need for a standardized testing method for fiber orientation measurement and suggests that UHPC codes should incorporate minimum requirements for fiber orientation. By including this factor in the design process, UHPC structures can achieve better performance and longer service life. Moreover, this article also discusses on the future research plan along with the recommendation for future works.

2. State of the Art Review of UHPC Placement and Fiber Orientation

In the literature, extensive studies showed the influence of casting directions, casting devices, formwork geometries, and fresh properties of UHPC had a great influence on fiber orientation and ultimately the mechanical performance of UHPC. However, the fiber orientation in structural scale UHPC members has not been fully investigated. Only limited investigations on the structural-scale (large-scale) members were reported in the literature in which the researchers applied realistic casting procedures and then either measured fiber orientation employing different methods or performed mechanical testing to verify fiber orientation or both (Yang et al. 2010, de Andrade et al. 2021, Yoo and Yoon 2015, Singh et al. 2017, Hasgul et al. 2018).

For realistic casting of longitudinal members, such as beams and piles, the UHPC is typically placed using two methods, i.e. (1) placed from one end of the form and allowed to flow to the other end to complete the filling process, (2) placed from the midspan and allowed to flow to both ends of the form (Figure 1). For relatively large-scale longitudinal specimens, literature shows that casting from one end and letting it flow to the other ends improves the fiber alignment along flow direction which is the principal stress direction. When casting from the middle, the fibers are less aligned due to a shorter flow distance.

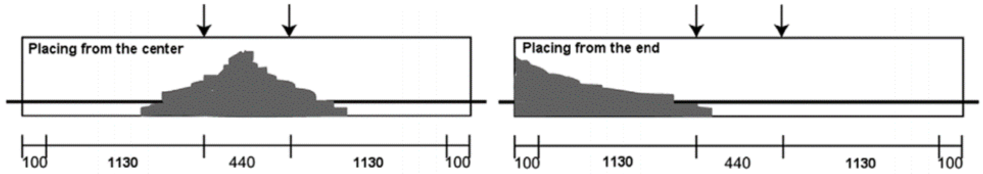

Figure 1 Procedure for placing the UHPC (Yang et al. 2010)

The formwork geometry also has a significant effect on the fiber orientation, as the formwork sidewalls and base tend to orient the fibers parallel to them during casting. As per AFGC recommendations ((Recommendation on Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC) by The Association Française de Génie Civil or French Association for Civil Engineering or AFGC, 2002 and 2013) fibers near formwork walls are naturally aligned parallel to the formwork which is called the wall effect. It only occurs when the distance from the formwork is less than or equal to the length of the fibers. The fiber orientation in narrow or thin sections of a large structural member, e.g., web and flange of I-girder or π-girder, is influenced due to the wall effect. Since the wall effect occurs near the formwork walls and narrow sections, the effect of the formwork sidewalls on the fiber alignment along UHPC flow direction is higher which is advantageous for the mechanical performance. However, in large-scale specimens with wide sections, the advantage of the wall effect on fiber alignment along the longitudinal direction is lower and the effect of fiber orientation on flexural performance is generally lower compared to narrow sections. As a result, the mechanical strength obtained from small-scale tests may not accurately reflect that of the real structures. Therefore, many UHPC design specifications consider adjusting fiber orientation based on the geometry of the elements.

For large flat specimens, i.e., bridge decks, panels or pavements, the UHPC casting flow from the middle of a circular specimen tends to align the fibers tangentially or perpendicularly to the flow direction while casting from one end tends to align the fibers along the flow direction (Kim et al. 2008, Barnett et al. 2010, Zhou and Uchida 2017, Ferrara et al. 2011, Nguyen et al. 2017). On the other hand, for panels poured randomly, the fibers were oriented randomly. The longer flow distance allows the fibers to align the fibers along the flow direction which increases the fiber alignment as well as mechanical properties along the flow direction.

The casting devices for large scale UHPC construction includes inclined chute or half-pipe from concrete mixing truck, vertical flow from a chute or half pipe from UHPC mix carrying Tuckerbilt buggy, casting using an inclined channel, casting using a wheelbarrow, casting using hopper hanging from a crane in the field, casting using a plastic bucket, using portable pan mixer at the formwork, etc (Islam et al. 2022). Figure 2 shows typical casting devices used in the construction sites. The most commonly used casting device is the inclined chute or half pipe which can be used to cast from the end or at the middle of the longitudinal UHPC structural members. The inclined chute has been reported to improve the fiber alignment.

(a) (b) (c)

Figure 2 Different casting devices for large scale UHPC construction (a) inclined chute or half-pipe from concrete mixing truck in the field, (source: Cor-Tuf), (b) casting using hopper hanging from a crane in the field (source: Cor-Tuf), and (c) casting using a wheelbarrow, (source: New York Department of Transportation).

3. Fiber Orientation Factor in Design Codes

The above state of the art review evidently reveals the effect of fiber orientation and dispersion on the strength and performance of UHPC construction based on UHPC placement methods, casting processes and casting devices.

The Association Française de Génie Civil (French Association for Civil Engineering) or AFGC recommendation was the first to introduce the fiber orientation factor to address the effect of fiber dispersion and orientation. These Recommendations on UHPC were intended to constitute a reference document serving as a basis for the use of UHPC as the new material in civil engineering applications and was published by the AFGC/SETRA in January 2002 and revised in 2013. In this recommendation, the fiber orientation factor is considered in the constitutive model of UHPC and the structural design of UHPC structures. As per AFGC recommendation (2002 and 2013), the fiber orientation factor K is a reduction factor to take into account the difference between the fiber orientation of the cast prisms that are used to determine the material property and the actual orientation of the fibers in the structure. Two K factors are defined: a local value and a global value. K_{local} (=1.75) is used when stresses of very localized areas (for example, prestressing stress distribution at anchorage zone) are of concern. K_{global} (=1.25) is used when the overall effects in larger areas (for example, the shear or the bending strength of a slab) are of concern, which will not be affected by a local defect. To obtain the K-factors, direct tensile tests or four-point bending tests are carried out on sawn prisms from the actual structure or a representative model (mock-up) built during the suitability tests prior to the construction and lab cast prisms and calculated by the ration of moment or force of lab cast prism and sawn prism from mock-up specimen. K_{global} is then calculated by taking the ratio between the average tensile/flexural strength of the cast specimens to that of the saw cut specimens, and K_{local} is calculated by taking the ratio between the average tensile/flexural strength of the cast specimens to the minimum value of the measured tensile/flexural strength of the saw cut specimens.

In addition to AFGC Recommendations, the fib Model Code (2010)) and the Canadian Highway Bridge Design Code (2019) (CSA S6:19) also introduced fiber orientation factors with similar concept. These design codes also provided alternative theoretical values for the fiber orientation factors in absence of a mock-up test.

On the other hand, design codes in North America took a different approach. For the structural design of UHPC structural members, the AASHTO LRFD guide specification for structural design with UHPC (2021, proposed version that is developed in consultation with AASHTO CBS T-10

(Structural Concrete Design) developed by researchers at the FHWA Turner-Fairbank Highway Research Center) and Concrete materials and methods of concrete construction/Test methods and standard practices for concrete (CSA A23, 2019) do not take fiber orientation into account. The Proposed Draft Version of AASHTO LRFD Guide Specification for Structural Design with Ultra-High Performance Concrete (Version 1.0) does not consider the orientation of fiber in the design of UHPC structural members. However, it discusses the following issues regarding the fiber orientation and dispersion in the UHPC structure: (a) The tensile resistance behavior of UHPC is dependent on the distribution and orientation of the fiber reinforcement in the UHPC which relies on the use of appropriate construction methods to ensure that the fiber reinforcement is evenly dispersed through the member and does not exhibit an undesirable orientational preference, (b) In this context, the contract documents should require the use of appropriate construction methods and the casting processes should be considered by the Design Professional to ensure that the member can be constructed, (c) the 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 and should be avoided.

4. Discussion

Measuring the effect of fiber orientation in UHPC is complicated. The AFGC Guideline and the French National Standards are generally accepted as the most reliable methods. The K factor, an approximation of the effect of fiber orientation on mechanical performance, is simple for design engineers to include into their design processes. The K factor and suitability test design approach have been employed productively by French UHPC projects to enhance casting practices. Nevertheless, the added expense incurred by UHPC structures as a result of these compatibility evaluations via suitability test using mock-up specimens may discourage certain industry groups and standards bodies from adopting this strategy. By enabling fiber orientation parameters to be computed using theoretical values or historical experimental data, the fib Model Code (2010) and CSA-S6 (2019) provide alternatives to expensive compatibility testing.

In North America, fiber orientation is not considered in UHPC design requirements. Designers must instead work on the assumption that fiber orientations will be determined at random during construction. Since it is a performance-based design code, AASHTO LRFD for UHPC (2021, proposed version) only provides the performance requirements for structural sections.

Although allowing more creativity in the design process, the AASHTO LRFD for UHPC (2021, proposed version) may also generate concern and tension in the minds of architects, engineers, and the precast industry as a whole. The effect of casting methods and formwork geometries on fiber orientation and structural performance has seldom been analyzed quantitatively or assessed. Further study is required to identify the best casting techniques for various member types and to develop casting devices that promote better fiber alignment.

Fiber orientation evaluation on prototypes of typical UHPC bridge sections is one such option. Fiber orientation variables for these sections might be recommended for use in UHPC design if this data is gathered and analyzed. By applying these findings to future projects with similar geometry, the need for repeated suitability testing will be avoided.

5. Plan for the Future Work

Currently, the authors are working on a research project to quantify the fiber orientation of UHPC in real structures and to derive fiber orientation factors to be used in the design for standard shapes. In this ongoing project, typical UHPC shapes, including a standard I-beam and a standard H-pile will be cast at partnering precast plants following several alternative procedures, and the fiber orientation will be quantified through imaging techniques, and sawn specimens will be extracted from the sections and tested for their tensile and flexural strength to derive the appropriate fiber orientation factors for design of similar sections. In addition, the reliability and effectiveness of the casting procedure will also be assessed, and necessary modification and optimization of the casting procedure will be conducted. This project is expected to improve the understanding of fiber orientations in large scale structures and increase the confidence of designers, owners, and contractors on the design of these UHPC members.

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