Fiber Orientation in Ultra-High-Performance Concrete (UHPC) Shear Connections in
Adjacent Box Beam Bridges

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the faculty of
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Master of Science

Nathan J. Hicks
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This thesis titled
Fiber Orientation in Ultra-High-Performance Concrete (UHPC) Shear Connections in
Adjacent Box Beam Bridges

by

NATHAN J. HICKS

has been approved for
the Department of Civil Engineering
and the Russ College of Engineering and Technology by

Kenneth K. Walsh
Assistant Professor of Civil Engineering

Dennis Irwin
Dean, Russ College of Engineering and Technology
ABSTRACT

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Fiber Orientation in Ultra-High-Performance Concrete (UHPC) Shear Connections in Adjacent Box Beam Bridges

Director of Thesis: Kenneth K. Walsh

Replacing the grout used in adjacent box beam shear connections with Ultra-High-Performance Concrete (UHPC) could potentially reduce or eliminate joint cracking, thus increasing the bridge’s lifespan and reducing maintenance costs. The strength of UHPC is influenced by the orientation of the small reinforcing fibers, added to increase ductility and energy absorption, relative to the stresses. This thesis presents an investigation of the fiber orientation within a UHPC shear key in order to determine how fibers interact with additional reinforcement, and align within the joint. Shear key cores were analyzed using a Micro-CT method to determine the fiber orientation. Fibers tended to align parallel to the flow direction, except in transverse reinforcement locations. Zones with very few fibers were also found under the transverse reinforcing bars due to the build-up of fibers on the reinforcement.
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CHAPTER 1: INTRODUCTION

One problem with prestressed concrete box beam bridges is the strength and durability of the grouted shear keys that connect adjacent beams. In order to improve the performance and service life of these structures, the use of a relatively new very high strength concrete in these connections is being investigated. This thesis focuses on an investigation of the concrete when used in an adjacent box beam shear key. This chapter will provide an introduction to this material as well as to adjacent box beam bridges, and will end with an overview of the remaining chapters of this document.

1.1 Introduction to Ultra High Performance Concrete (UHPC)

Developed in France in the 1990’s, Ultra High Performance Concrete (UHPC), also known as Reactive Powder Concrete (RPC), exhibits enhanced mechanical properties compared to conventional concrete (Buchman & Ignaton, 2010). UHPC is a form of concrete that is capable of achieving compressive strengths of approximately 22 ksi to 35 ksi (150 MPa to 250 MPa). These high strengths are achieved by changing several components of typical concrete mixes. Unlike conventional concrete, UHPC consists of only fine aggregates, such as silica sand, in addition to fly ash or silica fume. UHPC also has a very low water-cement ratio (<0.2) achieved by the addition of superplasticizers that increase the workability of the mix (Barnett et al, 2009). The elimination of course aggregates in UHPC results in a very dense and much less porous material, making UHPC much more resistant to water penetration, chemical attack, as well as freeze-thaw damage (Wille et al, 2011).
The extremely high compressive strengths achieved by UHPC also result in a very brittle failure mechanism. In order to increase the ductility of the material, short steel fibers are added during the mixing process. These fibers bridge any cracks that form before they are able to grow, greatly increasing the amount of energy that the material can absorb (Kang & Kim, 2011). The increase in energy absorption results in a much higher toughness and a more durable material, which is critical for a safe building material.

One of the most important properties of UHPC is the high post-cracking tensile strength that results from the addition of the steel fibers. Unlike conventional concrete, which exhibits a strain softening behavior, UHPC can exhibit strain hardening due to the fibers bridging micro-cracks as well as localized cracks that form during loading. Once cracking occurs, the fibers begin to carry an increased amount of the load which results in a continued increase in strength until the fibers begin to fail or debond from the concrete (Wille et al, 2014). This increase in post-cracking tensile strength also results in a much higher flexural strength. However, these increases in tensile and flexural strength are highly dependent on the orientation of the fibers in the UHPC relative to the direction of the principle stresses. A higher number of fibers aligned in the direction of the principle stresses will result in higher strengths as more fibers are able to bridge cracks that form under loading. The effect of fiber orientation on strength will be discussed in more detail in Chapter 2.

While the main use of UHPC has been for research purposes, there has been an increase in non-research related use in recent years. There are two main drawbacks to
UHPC that have caused this. The first is cost; the price of UHPC can be as much as 46 times higher than conventional concrete (Perry & Seibert, 2011). This makes its use in large structural members difficult. The second drawback is a lack of accepted design procedures. Although several design recommendations exist such as the French AFGC and Japanese JSCE, there are no widely accepted design guidelines for the use of UHPC in structural members. Until design guidelines are created, the use of UHPC will likely remain limited.

1.2 Introduction to Adjacent Box Beam Bridge Connections

Adjacent box beam bridges make up just over 8.5% of the bridges in the United States, making them one of the most used bridge types in the country (FHWA, 2013). These bridges are constructed by placing several box beams next to each other and connecting them through longitudinal grouted shear keys. Transverse post-tensioning is also typically used to help hold the beams together. A typical cross-section of an adjacent box beam bridge is shown in Figure 1.1.

![Figure 1.1. Typical cross-section of adjacent box beam bridge.](image-url)
The grouted shear keys frequently crack during service with cracking along the full length of the bridge being common. There are two shear key configurations typically used; partial-depth and full-depth. A partial-depth shear key is typically grouted in only the top portion of the box beam, while a full-depth shear key contains grout through the entire gap between beams as shown in Figure 1.2.

![Figure 1.2. a) Partial-depth shear key. b) Full-depth shear key.](image)

Research on cracking in shear keys has found that utilizing full-depth shear keys can reduce cracking of the joint by a large amount. Inspection of adjacent box beam bridges in New York found that only 5% of full-depth shear keys showed cracking while 54% of partial-depth shear keys had cracked (Lall et al, 1998). There are multiple possible causes of shear key cracking including bearing pad design, amount and location of transverse post tensioning, as well as the grout type and the construction process (de Murphy et al, 2010).

Cracking of the shear key can lead to several problems that have the potential to reduce the structural integrity of the bridge unless they are caught during inspections. The main purpose of the shear key is to transfer shear forces from one box beam to the one
adjacent to it. This load transfer ensures that the bridge works as a single structural system rather than several individual beams. A cracked shear key can result in a reduction of load transfer, which can then subject individual box beams to higher loads than they were designed for. Relative displacement between beams can then cause cracking of the road surface and any waterproofing system between the beams and the road, which will allow water and deicing chemicals to enter the keyway.

If the water is then able to reach the reinforcement within the box beams, corrosion can result in a loss of effectiveness and a further reduction in strength. In addition, expansion of the water due to freezing can cause additional cracking which can allow even more water to enter the joint further exacerbating the problem.

1.3 Problem Statement

The enhanced material properties of UHPC make it a possible candidate to replace the grout typically used in adjacent box beam shear keys. UHPC has been used in box beam shear keys in several bridges in Canada, as well as in connections between precast bridge deck panels in Iowa, New York, and Canada (Lafarge North America; Heimann, 2013). While UHPC has been used for several joint fill applications, no research has been conducted on the material itself when used for this purpose other than evaluating the overall performance of the bridge once opened to traffic. As previously mentioned, the material properties of UHPC are influenced by the fiber orientation, and a large amount of research has been conducted on determining fiber orientation in UHPC and other fiber reinforced concretes. However, to date there has been no research
conducted on the fiber orientation within box beam shear keys or how mild steel reinforcement affects the fiber orientation.

The goals of this research are to determine how the fibers align within the shear key of an adjacent box beam bridge and how the orientation varies through the depth of the shear key. In addition, the interaction between the fibers and transverse reinforcement within the joint, as well as wall effects within the shear key will be investigated.

1.4 Research Methods

In order to answer the above questions, an experimental program was developed to directly measure the fiber orientation within a box beam shear key. The experimental program is briefly described below, with detailed information presented in Chapter 3.

1.4.1 Sollars Road Bridge, Fayette County, Ohio

Bridge number FAY-C0004-0160 is located on Sollars Road near Washington Courthouse in Fayette County, OH. Built in 1964, the original structure was a simply supported concrete box beam bridge with a 50’-5” span. This bridge was replaced in July of 2014 with a similar design with several important differences. The new bridge is a prestressed concrete box beam with a 60’-0” span length. In addition to a longer span, the new structure differs from the old mainly in the design of the shear keys. The shear keys in the new bridge replicate the design used in a testing program conducted by the Federal Highway Administration at the Turner-Fairbank Highway Research Center. In addition to a different shape, closely spaced transverse dowel bars were used to reinforce the joints and no transverse tie rods or post tensioning was used.
In place of the typical grout used in box beam bridges, the shear keys were filled with Ductal® JS1000 UHPC produced by Lafarge North America. Being the first bridge in the United States to utilize UHPC for box beam shear keys, this provided an excellent opportunity to investigate the fiber orientation in a fairly new application for UHPC under the conditions present in an actual structure.

1.4.2 Determining Fiber Orientation

A 3D method that utilizes micro-CT (µCT) scans of small samples was utilized to determine the fiber orientation. To do this, small samples are taken from within the shear key at areas of interest and placed into a µCT scanner where X-Rays are used to create a 3D image of the entire volume of the sample. An image analysis program called Avizo Fire was then used to analyze these images and measure the orientation of each fiber in the samples.

1.4.3 Obtaining Samples

Since removing pieces of the actual bridge shear keys was not an option, an exact replica of the shear key was created using dimensions obtained from the precast manufacturer. Several replicas were created so that the dowel bar spacing could be changed in order to investigate the effect of spacing on fiber orientation. Because the dowel bars and the fibers have similar densities, it would be difficult to distinguish fibers that are very close to the dowel bars in the µCT images. To avoid this potential problem, dowel bars were replicated using resin so that the shape of the steel dowels could be maintained, but the interaction between the dowels and the fibers could be studied. The
replicas were built at Ohio University prior to the construction of the new bridge, and transported to the construction site the day before the shear keys were filled with UHPC.

After the bridge joints were filled, UHPC was used to fill the replicas. This allowed the conditions present in the actual bridge to be matched as closely as possible. After allowing time for the UHPC to harden, the replicas were transported back to Ohio University for analysis. Cores with a diameter of 1.25 in. were taken in several locations using a diamond tipped core bit. These cores were then cut to a reasonable length before performing the CT scans.

1.4.4 Data Analysis

Three different methods were used to determine the overall fiber orientation within each sample. The first is through a value known as the orientation number, which measures how parallel the fibers are to a specified axis. The second method uses a probability density histogram and accompanying probability density function (PDF) created using the fiber orientation data obtained from the image analysis. The final method used to determine the overall fiber orientation is using alignment tensors. The average orientation is found by determining the eigenvalues and eigenvectors of a second-degree tensor created with the orientation data for each fiber.

1.4.5 Introduction to Remaining Chapters

The remainder of this thesis will provide detailed information about the experiment conducted and the results obtained. Chapter 2 provides a more detailed look at previous research conducted on UHPC as well as work related to fiber-reinforced composites. Chapter 3 describes the experimental procedure in detail. This includes the
results of two cube samples that were analyzed in order to gain familiarity with the methodology as well as develop and test Matlab codes used for the data analysis. Chapter 4 will present and discuss the results of the data analysis performed on the samples taken from the shear key replicas, and Chapter 5 will discuss the conclusions that were drawn about the fiber orientation within a box beam shear key.
CHAPTER 2: BACKGROUND

Introduction

In this chapter, previous research pertaining to the use and development of Ultra-High Performance Concrete (UHPC) for civil engineering applications will be discussed. The goal is to determine the issues associated with the use of UHPC, as it has not been widely used in past or current construction projects. A general overview of the use of UHPC in structural engineering will be given as well as more specific research pertaining to its use in bridges and buildings, as those two types of structures make up the majority of structures built with concrete. Building on the overview of UHPC, research related to the fiber reinforcement in UHPC will also be discussed, as it is an important part of this material.

2.1 UHPC Applications in Structural Engineering

With the deteriorated state of civil infrastructure and the increase in the number of tall buildings, long-span bridges, and the need to reduce the lifecycle costs of structures, there are many areas in structural engineering that can benefit from the use of UHPC. In addition to use in typical structures, the possible use of UHPC in other structures has also been investigated. This section will discuss past research on the applications of UHPC in structural elements.

2.1.1 General and Special Applications

Corrosion of steel reinforcement due to penetration of water and chloride ions, as well as freeze-thaw damage, are two of the leading causes of early damage in concrete structures (Mohamed et al, 2012; Yang et al, 2006). This problem is especially prevalent
in bridges, where the deck and superstructure are frequently exposed to water and chlorides from winter deicing operations. Over time water can work its way through voids in the concrete, eventually reaching the steel reinforcement. When this happens, chloride ions carried by the water can lead to very high corrosion rates of the steel which causes a loss of cross sectional area and a reduction in its effectiveness. An increased number of cracks caused by freeze-thaw cycles can increase liquid penetration and corrosion. As previously mentioned, the high density of UHPC makes it extremely resistant to liquid penetration. Permeability tests conducted on UHPC samples showed that a crack opening of 0.13 mm was required before water penetration increased significantly, compared to 0.05 mm for normal concrete (Charron et al, 2007). With a required crack opening more than twice as large as normal concrete, in addition to its much higher strength, UHPC is much less likely to be affected by chloride penetration or freeze-thaw damage. Using a thin layer of UHPC on the outside of structural members would greatly reduce the possibility of water damage.

Because of its high strength and its ability to flow into formwork, UHPC has the ability to be cast into non-standard shapes and be used in thin plate or shell elements. Using a thin element can result in a significant weight reduction and therefore reduce the size of the structural members required to support them. UHPC has successfully been used in a thin-shell roof for a train station in Canada. The roof system is made up of large UHPC shells only 20 mm (0.75 in.) thick. The reduced weight allows each panel to be supported by a single column, which also contains cables for lighting and other electrical systems (Vicenzino et al, 2005). In order to investigate the flexural strength of thin
UHPC roof panels, di Prisco et al (2008) performed flexural tests on several thin UHPC plates. The authors found that the plates exhibited hardening behavior in bending. The bearing capacity predicted using Italian design guidelines was much lower than observed, while the predicted ductility was fairly accurate.

UHPC has also been investigated for use in thin cladding panels for building facades (Remy et al., 2008), lightweight bridge decks (Saleem et al, 2011), as well as a large arch structure to cover a pedestrian bridge (Terzijski, 2008) with promising results. While the results of the aforementioned studies are encouraging, further research is needed to more accurately determine the effect of span length and thickness on thin elements so that engineers can design appropriately sized elements and still ensure the safety of the structures.

Another potential use for UHPC is in blast protection panels for structures in dangerous regions. Researchers in Australia examined the performance of UHPC panels subjected to blast and projectile impact loads. Several panels with varying thicknesses were subjected to large explosions at multiple distances. Another experiment tested the ability of 100 mm thick UHPC panels to resist standard and armor piercing projectiles. In both experiments, the panels were able to successfully resist the explosions and projectiles with no fragmentation of the panels. Based on the results of these tests, the Australian Department of Foreign Affairs and Trade purchased 100 mm thick UHPC panels for a blast protection system for an existing building (Rebentrost & Wight, 2008).

UHPC has also been successfully used in the foundations of offshore wind turbine foundations. The UHPC is used to connect the turbine monopole to the underwater
foundation by sealing the area and pumping the UHPC from the surface into the foundation (Moeller, 2008).

2.1.2 Bridge Applications

The previously mentioned properties of UHPC make it an especially useful material for bridges. With nearly 25% of bridges in the United States classified as either structurally deficient or functionally obsolete (ASCE, 2013), a large amount of bridge rehabilitation and construction will need to take place over the next decade. Bridge engineers are always looking for ways to get the most performance out of the materials used in a structure, while bridge owners are looking for ways to reduce the costs of bridges both up front as well as over the lifetime of the structure. UHPC has the potential to address both of these problems.

The high strength and durability of UHPC could lend themselves very well to use in both superstructure and substructure elements in bridges. But before it can be used in the key structural elements, its mechanical behavior must be fully understood and design standards must be developed (Walraven, 2009). While many researchers have performed standard compression, bending, and tensile tests on UHPC specimens, few have performed large-scale tests to determine the performance of full-sized structural members. The standard material test are important to determine the basic material properties, but full scale tests are also needed to verify that the material retains those properties on a much larger scale, and to aid in developing design guidelines. To date, several large-scale experiments have been performed in an attempt to investigate the
performance of full-scale structural members and develop models to predict the strength of these members.

Prestressed I-Beams and T-Beams are frequently used in bridges around the world. Recent research on these two types of bridge beams made with UHPC has shown good results. The U.S. Federal Highway Administration (FHWA) has conducted flexural and shear tests on several AASHTO Type II prestressed I-Girders. Finite Element Analysis (FEA) was also used to create Concrete Damaged Plasticity (CDP) and Concrete Smeared Cracking (CSC) models to accurately describe the material behavior. The analytical results were consistent with experimental results for different span lengths showing that the CDP and CSC models were adequate to predict the material response (Chen & Graybeal, 2012B). Flexural tests have also been conducted on several full size prestressed UHPC T-Beams. Three T-Beams with varying depths and span lengths were tested in four point bending tests. Analytical work based on beam theory was also done in an attempt to predict the flexural strength of the beams. The strain-softening behavior of the concrete matrix was accounted for in the analytical analysis using an inverse analysis based on previous work by Kitsutaka (1997), and Uchida and Barr (1998). The results of the physical tests and analytical analysis agreed well, with the analytical results varying from the physical tests by approximately ±20% (Yang et al, 2011). These experiments are very important for the potential use of UHPC in future bridge superstructure components.

The previously mentioned CDP and CSC models have also been applied to second generation prestressed pi-girders. Transverse flexural tests were conducted on a full size pi-girder as well as a connection between two girders, and the FEA models were
then used to replicate the experimental tests. The CDP model performed fairly well while the CSC model was not able to replicate the experimental results for lower loads. Based on these experiments, several improved cross-sections were developed that meet AASHTO strength and serviceability requirements (Chen & Graybeal, 2012A). The results of these experiments show that UHPC can be effectively used in bridge girders of varying span lengths. Smaller sections or longer spans can be designed which can in turn reduce the substructure requirements of bridges.

In addition to being used in the construction of large structural members, UHPC can also be used very effectively in field-cast connections between bridge components. The properties of UHPC allow simple connections to be designed and greatly reduce the amount of concrete needed for the connections. These connections are much stronger than typical field-cast connections and greatly improve the strength of the joint as well as the entire structural system. The use of precast components has increased in recent years due to the reduced construction time, cost, and higher quality. Tests performed at the FHWA Turner Fairbank Highway Research Center found that precast decks with either transverse or longitudinal UHPC connections performed as well as or better than a cast-in-place deck (Graybeal, 2010).

Other non-structural bridge components can also benefit from UHPC’s properties. Parapets are extremely important for the safety of the users of the bridge as well as anything below the bridge. The high cost of UHPC makes it uneconomical to construct parapets entirely of UHPC. Researchers in Canada designed a precast composite parapet that consists of an inner core of normal strength concrete, and a thin outer layer of UHPC.
The thickness of the UHPC layer varied depending on the location on the parapet. The high strength of the UHPC also allowed conventional reinforcement within the core to be eliminated. This hybrid parapet was able to achieve a 54% increase in ultimate strength over the AASHTO requirements (Duchesneau et al, 2011). Therefore, it is possible to use UHPC for parapets in an economical way that provides adequate strength as well as protection from corrosion.

Although UHPC is being used more frequently in Europe, it is only beginning to be used in the United States. The main reason for this is the much higher cost. While it may seem that UHPC is too expensive to be used for large projects, its properties allow the design of smaller cross sections, which require less material and therefore lower costs. While smaller components can reduce costs, it is difficult and potentially more costly to design these smaller sections due to a lack of design procedures for UHPC. The design procedures that most bridge designers are familiar with from the AASHTO LRFD Bridge Design Specification are only valid for concrete strengths up to 10 ksi unless tests are done to establish relationships between the strength and other material properties (AASHTO, 2010). To date, several researchers have attempted to develop design procedures for UHPC.

Researchers in Canada have proposed a design method for simply supported slab-on-girder bridges based on the Canadian Highway Bridge Design Code (CHBCD) as well as French and Japanese design recommendations for UHPC (AFGC 2002 & JSCE 2006). Because of a lack of data on the performance of UHPC Girders, the designs were very conservative. The iterative design procedure includes a simplified analysis and design
procedure based on the French and Canadian specifications and then a refined analysis conducted using a linear elastic FEA. The developed procedure was used to design a simple bridge and the resulting design was then compared to the design of a bridge that utilized High Performance Concrete (HPC) girders. The two bridges had the same geometric properties including span length, slab thickness, number of lanes, boundary conditions, and loading cases. The resulting UHPC bridge required two less girders, and also reduced the girder depth from 55 in. to 35 in., resulting in a 32% reduction in the weight of the superstructure (Almansour & Lounis, 2010).

By reducing the weight of the superstructure, the size of the substructure and foundations can also be reduced, which will lower the cost of the bridge. With the large number of bridges that will need to be replaced in coming years, any reductions in costs will allow more bridges to be repaired or constructed with the available funding.

Other research has been conducted to determine the validity of several design methods for use with UHPC. Steinberg (2010) performed Monte Carlo simulations in order to determine the reliability of several methods to determine the flexural strength of UHPC girders. The results of the analysis showed that the design equations in the AASHTO Bridge Design Specification provided the most conservative and most consistent results. Although the AASHTO method is slightly over conservative due to it ignoring the tensile strength of the UHPC, until more data is available on the performance of UHPC, the AASHTO equations that most bridge designers are familiar with provide an adequate design (Steinberg, 2010).
2.1.3 Building Applications

While the properties of UHPC are especially useful for bridges where the structural elements are exposed to the environment, it can also be extremely useful in buildings. In 2013 alone, 73 buildings were completed with heights of 200 m or higher, and 63% of those were constructed using concrete (Council on Tall Buildings and Urban Habitat, 2013). As the height and number of tall buildings increases, the need for more advanced building materials will become very important. With its significantly higher strength and durability, UHPC is a material that could fill that role in future structures.

In high-rise structures in particular, usable floor space comes at a premium. More open space allows better views and increased income for the building owner among other things. The sometimes large columns required to support the building cannot always be hidden inside walls and consequently take up valuable floor space. Utilizing UHPC in some or all of these columns would allow smaller sections to be used and open up valuable floor space in the building. Several researchers have looked at the performance of several different types of UHPC columns to determine their behavior.

Empelmann et al (2008) investigated short square UHPC columns with varying amounts and patterns of steel reinforcement in addition to steel fibers. The results of the experiments showed that in most cases the UHPC columns were more ductile than typical reinforced concrete columns. Based on the results, the authors developed recommendations for fiber content, minimum lateral reinforcement, and minimum load supported by longitudinal reinforcement for square UHPC columns.
Research has also been conducted on tubular steel columns filled with UHPC. Confining the UHPC within a steel column eliminates the need for internal steel reinforcement and eliminates the possibility of a brittle failure. In an experiment on several steel encased UHPC columns, the columns exhibited much higher ductility than an unconfined UHPC column, while the confining effect of the steel tube is lower than with normal strength concrete (Yan & Feng, 2008).

Other research on composite steel-concrete columns has compared both UHPC filled steel columns and normal strength concrete filled steel columns. Liew and Xiong (2012) found that the strength and ductility of composite columns can be improved if the load is applied to only the concrete, and/or a minimum of 1% steel fibers is added to the mix. These studies indicate that UHPC can be safely used in multiple configurations in many different structures in order to reduce column size. Although the studies have shown good results, further research is needed to develop appropriate design procedures for UHPC columns. While most research conducted is performed with concentric loading, many columns in buildings are subjected to biaxial loading. Curbach and Speck (2008) conducted biaxial compression tests on UHPC samples to determine the behavior under multi-axial loading. They found that the UHPC is less brittle under biaxial loading than under uniaxial loading and that a fiber content around 2.5% is needed for adequate crack control.

In addition to its high strength and durability, UHPC also has very high bond strength, which makes it ideal for field cast connections. This high bond strength also has the potential to greatly reduce the required development lengths for reinforcement within
the connections. In an attempt to determine effective development lengths for high strength steel rebar embedded in UHPC, Saleem et al (2013) conducted pullout tests on number 10 and 22 rebar in UHPC. The large rebar sizes were chosen to replicate the conditions in a related project for a lightweight bridge deck. Several different embedment lengths were tested for both bar sizes and the results were compared to the recommended development lengths from the ACI 318-08, ACI 408R-03, and AASHTO design codes. The tests showed that the ACI 318 and AASHTO development lengths were much higher than those used in the study, while the ACI 408R development lengths were much closer, although still slightly higher. The authors concluded that an initial estimate of 12\(d_b\) for number 10 bars and 18\(d_b\) for number 22 bars can be used where \(d_b\) is the bar diameter (Saleem et al, 2013). While more tests on other rebar sizes are needed before development length guidelines can be proposed, these results show that the bond strength of UHPC is much higher than normal strength concrete which allows much shorter development lengths.

Further research on UHPC connections has shown that it could be used for continuity connections between precast beam elements as well as beam-column connections for moment frames. Very short reinforcement splice lengths were adequate to achieve the expected ultimate strengths of the spliced beams as well as the moment connections (Maya et al, 2013). Utilizing precast structural elements can greatly reduce the time required for construction as well as project cost. Using UHPC for connections between precast elements can further reduce the amount of labor required to construct buildings, as well as making it possible to use precast components for things such as
moment frames or long span beams that may not have been feasible with normal or high
strength concrete.

Because of its high cost compared to normal strength concrete, UHPC has the
potential to be used in composite construction where the total amount of material used is
greatly reduced. Several researchers have investigated using UHPC in composite
structural members. Schäfers and Seim (2008) found that adding a thin UHPC plate to the
top and bottom of timber beams can increase the flexural strength by five to six times.
Hegger and Rauscher (2008) investigated continuous shear connections for composite
beams. They discovered that the continuous “puzzle strip” shear connector was able to
transfer very large shear forces, and that adding transverse reinforcement within the
strip’s recesses increased the ultimate load capacity by 30%. Other researchers have
investigated using UHPC planks on the top and bottom of glued-laminated timber
(Glulam) beams. It was found that the composite beams had a bending stiffness 40% to
60% higher than reference beams depending on the span length (Ferrier et al, 2010).
Utilizing UHPC in composite construction allows the superior mechanical properties of
the UHPC to be utilized while also keeping costs down.

2.2 Effect of Fiber Orientation on Mechanical Properties

Like all fiber-reinforced composites, the mechanical properties of UHPC are
influenced by the orientation of the fibers as well as the distribution of the fibers
throughout the cement matrix. Multiple researchers have found that the orientation of the
fibers has a significant effect on the strength of the material (Wang et al, 2014; Pansuk et
al, 2008; Kim et al, 2008). Because of this dependency on fiber orientation, it must either
be accounted for in the design of structural components, or shown that the resulting fiber orientation in full-scale components is satisfactory for the safety of the structures that they are used in. In order for UHPC to have uniform material properties, fibers would need to be randomly oriented in all directions. It has been found, however, that several factors can affect the orientation of the fibers including the formwork, specimen size, as well as the flow of the UHPC during pouring (Kang & Kim, 2011; Wille & Montesinos, 2012; Zerbino et al, 2011). Because the fibers are very small and there are a large number of them at different orientations, they have different effects on the different material properties.

2.2.1 Effects on Compressive Strength

One of the main benefits of adding steel fiber to UHPC is that it reduces the brittle failures that can occur under very high compressive loads. Without fibers, UHPC will fail very quickly and explosively, while UHPC with fibers shows greatly improved ductility (Liew & Xiong, 2012). Several authors have found that the addition of steel fibers leads to moderate increases in the compressive strength. Kazemi and Lubell (2012) found that adding 2% to 5% fibers by volume resulted in 5.8% to 25% increases in compressive strength. Other research has shown that an addition of 2.55% fibers increased the compressive strength by up to 16%, and an addition of 1.86% fibers resulted in a 17.65% increase (Magureanu et al, 2012; Buchman & Ignaton, 2010). Because the increase in compressive strength due to the fibers is relatively low and the compressive strength of the UHPC without fibers is already very high, little research has been conducted on the effect of fibers on the compressive strength. The main contribution of the fibers in
compression is to increase the energy absorption and eliminate catastrophic brittle failures.

2.2.2 Effects on Tensile and Flexural Strength

It is well known in the structural engineering field that concrete is very weak in tension; so much so that the tensile strength of normal strength concrete is neglected in the design of reinforce concrete components (ACI, 2011). One of the advantages of UHPC is its very high tensile strength relative to normal strength concrete, which typically has tensile strengths of around 300 psi to 700 psi, while UHPC has tensile strengths around 2000 psi (Graybeal & Hartmann, 2003). UHPC also exhibits a high post-cracking tensile strength due to the addition of the steel fibers. The increase in tensile strength is due to fiber crack bridging (Kang & Kim, 2011). This high strength after initial cracking is very important for the safety of structures built using UHPC as it provides advanced warning to occupants or users of the structure before a complete failure occurs. Empelmann et al (2008) found that using longer fibers can increase the post cracking tensile strength by 10% to 20%. Research on the tensile behavior of UHPC has shown that the fiber orientation relative to the stress direction has a very large effect on the tensile strength of the material (Kang & Kim, 2011). Despite its higher strength in tension, UHPC is still not suitable for use in members subjected to direct tension. For this reason, little research has been done on relating the fiber orientation to direct tensile strength. One study found that the direct tensile strength of a UHPC mix varied from around 1.5 ksi for a fiber content of 1.5% to around 2.9 ksi for a fiber content of 3%, and exhibited a significant strain hardening behavior (Wille et al, 2014).
In addition to direct tension, the tensile behavior is very important for the flexural strength of UHPC members. Since the properties of UHPC are dependent on the orientation of the reinforcing fibers, much research has been conducted on relating the fiber orientation to the flexural strength or flexural-tensile strength of UHPC.

Because UHPC is much less viscous than typical concrete, the flow of the UHPC during placement can have an effect on the alignment of the fibers (Deeb et al, 2013). By changing the placement method, different fiber orientations can be achieved and qualitatively related to the flexural strength of the specimen. In circular panels, specimens poured from the panel center exhibit the highest flexural strength due to fibers aligning perpendicular to the panel radius and bridging the radial cracks produced under loading. Conversely, panels poured from the edges and panels poured randomly showed the lowest and intermediate flexural strengths respectively (Barnett et al, 2010). In rectangular beams poured in a similar fashion, it has been found that placing the concrete in the direction of the flexural tension can result in an increase of around 50% in the ultimate strength, while a similar study found an increase of around 30% (Kim et al, 2008; Kang & Kim, 2011). These results indicate that the flow distance has a significant effect on the fiber orientation; namely that as the flow distance increases, fibers tend to align parallel to the flow direction. Another study found that in thin elements such as slabs or walls, the fibers were more aligned in locations that experienced higher flow rates. This resulted in significantly higher flexural strengths in the flow direction, and much lower strengths perpendicular to the flow direction. It was also discovered that the fiber alignment was much less uniform at the ends of the formwork resulting in a lower
flexural strength, although the strength was much more uniform in different directions (Zerbino et al, 2010). Other work on flexural strength has found that the addition of fibers can increase the flexural strength by 140% compared to no fibers (Magureanu et al, 2012). Buchman and Ignaton also found that adding 1.86% fibers resulted in a 106.5% increase in flexural strength while the compressive strength only increased by 17.65% (Buchman & Ignaton, 2010).

Although the majority of research conducted on UHPC has been done on the relationship between fiber orientation and flexural strength, only qualitative relationships have been found. Generally, it has been found that the highest flexural strength is achieved when the fibers are parallel to the flexural tensile direction. Attempting to develop quantitative relationships experimentally is difficult due to the many different fiber orientations found in a specimen. In order to develop this kind of relationship, many tests would need to be conducted with controlled fiber orientations, which is very difficult to do experimentally. Even though only qualitative relationships have been developed, the results from different experiments have been consistent. By pouring the UHPC in particular ways the average fiber orientation can be controlled. This allows designers to specify a placement method to achieve a desired fiber orientation that will provide the highest strength possible for a particular application.

2.2.3 Analytical and Finite Element Modeling

It is easy to determine if the fiber orientation has an effect on material properties in a qualitative way. However, it is much more difficult to quantitatively determine the effect of fiber orientation. The fiber orientation needs to be carefully controlled and
changed so that material properties at different orientations could be determined. This would be very difficult to do experimentally. However, this can be done easily using Finite Element Modeling (FEM). Using FEM, researchers can control the number of fibers, their distribution, orientation, and other factors. Using the properties of the different materials, simulations can be performed for many different fiber orientations in a fraction of the time and at a much lower cost than laboratory experiments.

FEM was utilized by Wang et al (2014) to investigate the effect of fiber orientation on the Young’s Modulus of glass fiber reinforced polymers (GFRP). Using the finite element program Abaqus, several models with different fiber orientations were subjected to uniaxial tension. The Young’s Modulus was then calculated for the different fiber orientations. It was found that the Young’s Modulus decreases as the fibers become more perpendicular to the loading direction. Other researchers have utilized laboratory mechanical testing in order to calibrate the finite element (FE) models in order to achieve the most accurate results. Guénet et al utilized a fracture micro-mechanics FEM to analyze the effect of fiber orientation on a UHPC bridge deck. A probability distribution function was used to describe the variation in the fiber orientation caused by different pouring methods (Guénet et al, 2013). Delsol and Charron used tensile and bending tests along with photo analysis to derive an empirical model to describe the tensile strength with respect to fiber orientation. This model was then used in FE models to investigate the behavior of structural elements (Delsol & Charron, 2013). In both of these cases, the FE models were able to accurately reproduce the experimental results.
Although FEM can allow simulations to be performed easily compared to laboratory tests, the process can become very slow when modeling UHPC with a large number of fibers. This increase in computation time is due to the meshes for the concrete and fibers being matched geometrically. When there are a large number of fibers, generating this mesh can be computationally intensive, which increases the time required to perform the analysis. In order to avoid this problem, Pros et al (2012) utilized a model based on an immersed boundary approach to model the fibers and concrete separately. This method models the fibers and concrete separately, and the two models interact during the simulation. This allows the exact fiber volume and orientation to be used without requiring a large conformal mesh for the entire model.

In all of these studies, the FE models were able to predict or reproduce the response of the UHPC for various loadings. For this reason, along with the versatility, any direct relationships between the fiber orientation and material properties will most likely be discovered through FEM and verified through laboratory tests.

2.3 Determination of Fiber Orientation

In order to relate the fiber orientation to the material properties, the orientation of the fibers relative to some reference must be determined. The large number of fibers and the density of the UHPC can make this a difficult task. Several methods have been devised to determine fiber orientation with differing levels of accuracy and effort required. The majority of the methods require the UHPC to be cut into small samples, making in situ testing on structural elements impossible. In addition, the analysis can be
very tedious and time consuming, which makes determining fiber orientation impractical for purposes other than research in most cases.

2.3.1 Photo Analysis Method

The simplest method of characterizing fiber orientation is an image analysis technique developed by Lee (2002). In order to determine the fiber orientation, the UHPC is cut into samples with dimensions at least as large as the fiber length. The cut faces of the samples are then polished so that the fibers are more visible as shown in Figure 2.1.

![Figure 2.1. UHPC sample before and after polishing. (Wuest et al, 2009)](image)

High-resolution pictures are then taken of the polished faces so that measurements can be performed in order to determine the orientation of the fibers. The fiber orientation can be calculated by measuring the major and minor axes of the ellipses formed by the fibers in the cut plane (Wuest et al, 2009). The photo analysis method is very simple and does not require large amounts of time to perform, but it can only provide a limited amount of information. Since only the fibers visible on a cut plane can be analyzed, no information about fibers that lie completely inside the sample can be obtained. A
complete description of fiber orientation within a sample can therefore not be obtained through photo analysis.

Lui et al (2013) compared results obtained from 2D photo analysis with the µCT method. They found that the two methods resulted in very similar orientation distributions, although the values were different. This was due to the 3D method producing more accurate results as it describes the fiber orientation in 3D space and does not rely on the quality of sample preparation. Wuest et al developed a method to determine the fiber orientation based on the number of fibers in a plane. Using photo analysis, the number of fibers in three orthogonal planes was determined. The average orientation of the fibers was then determined in the form of two angles. When applied to several tensile test specimens, the calculated orientations agreed with the results of the photo analysis with less than 7% error (Wuest et al, 2007).

2.3.2 Micro-CT Method

In order to look at the orientation of all of the fibers within a sample, a method that allows researcher to look into the sample without cutting it into many small pieces is needed. Micro-CT (µCT) is such a method. To investigate the fiber orientation using µCT, a UHPC specimen is cut into small samples. The size of the samples depends on the power of the CT scanner being used as well as the size of the scanning bed. Because UHPC is very dense, very high X-Ray energies are needed to achieve good penetration of the sample. If the energy is too low, the resulting images can contain artifacts such as beam hardening (Surronen et al, 2013) and streaking. These artifacts make the image processing very difficult and time consuming, although their effects can be reduced
through the use of image filters. The CT scans result in a three-dimensional volume image of the sample. These images can then be analyzed using commercial image analysis software. The software allows the fibers to be separated from the surrounding concrete matrix in a process call segmentation. The segmentation is performed by grouping the image voxels (3D pixels) based on the intensity of their gray values, and assigning the grouped objects to a specific material. Gray values are based on the density of the material, with higher gray values corresponding to high material density and lower gray values corresponding to less dense materials.

Being denser than the concrete, the steel fibers have much higher gray values and appear white in the images while the concrete is dark gray as seen in Figure 2.2.

![Figure 2.2. μCT scan of UHPC.](image)

It is possible for the image analysis programs to automatically segment the images based on user-defined values for the threshold between different materials. However, this typically is not possible with UHPC due to the small size of the fibers as well as their
close proximity to one another. When several fibers are very close together, the software is not always able to detect the lower gray values of the very small amount of concrete between them, and interprets the fibers as a single object. This becomes a problem after the segmentation is completed and measurements are performed on the segmented materials; where each fiber should be measured individually, some measurements are performed on large groups of fibers. The software is able to perform several measurements on the segmented fibers including length, volume, coordinates of the endpoints and gravity point, as well as orientation angles. In order to obtain accurate measurements, methods to separate connected fiber must be used, or the fibers can be segmented individually.

Micro-CT has been successfully used by several researchers to investigate fiber orientation in multiple types of specimens. Pujadas et al (2014) utilized µCT to study the effect of slab width on the orientation and distribution of polypropylene fibers. The number of fibers calculated from scans compared very well to the fiber dosage with a difference of only 0.12%. A method to separate fibers mistakenly connected during image segmentation was developed by Surronen et al (2013) using Matlab and Avizo Fire image analysis software with an accuracy of 95%. Micro-CT has also been used to investigate the voids in fiber-reinforced composites and found to be very accurate, provided the scans are of a high enough resolution (Little et al, 2011).

While the photo analysis and µCT methods are considered non-destructive, they still require the specimen to be cut into small pieces for analysis. This limits their use to research and eliminates their use in actual structural components. Though research results
can help predict how the fibers will align in a full size structural element, a way to inspect the fiber reinforcement in an element before it is put into service would be beneficial to ensure the quality and safety of the finished product.

2.3.3 Electrical Resistivity Method

One such way to investigate the fiber orientation in a non-destructive manner is through electrical resistivity measurements. This method aims to map the electrical properties of the UHPC, and then relate those properties to the fiber orientation. To measure the resistivity, a square array of electrical probes is attached to the specimen. A known current is then passed through two of the probes, while the other two probes measure the difference in electric potential caused by the current passing through the concrete. The apparent resistivity can then be calculated along with the electrical anisotropy, which is the ratio of resistivity in perpendicular directions. The electric properties are related to the fiber orientation through the anisotropy values; highly aligned fibers result in higher anisotropy values. By taking measurements in several directions and plotting the anisotropy values according to direction, the direction and intensity of anisotropy can be seen. The fiber orientation can be determined from the direction of electrical anisotropy in each location, with the fibers being aligned perpendicular to the axis of anisotropy.

The accuracy of the method was investigated by Lataste et al (2008). The authors found that the method was able to identify the pouring method, and consequently the general fiber orientation, in several slab specimens. The same method was later used on round panels and verified through µCT scans (Barnett et al, 2010). Although the method
is only able to determine the probable fiber orientation, it could potentially be used for
quality control of UHPC elements prior to their use. Any unreinforced areas or areas with
abnormal fiber orientations could easily be discovered without the need to cut into the
specimens.

2.3.4 AC-Impedance Spectroscopy Method

AC-Impedance Spectroscopy (AC-IS) is another non-destructive method that uses
the electrical properties of the UHPC to determine the fiber orientation. In AC-IS, an AC
current is applied to the surface of a sample through electrodes attached to the specimen.
The current is applied over a large range of frequencies and the impedance is measured
for each frequency. The measured impedance contains real and imaginary components
which are plotted on a Nyquist plot, which plots the negative imaginary component
versus the positive real component. The Nyquist plots obtained in the AC-IS method are
characterized by a ‘dual cusp’ behavior that results from the fiber behaving as insulators
at low frequency excitations and as conductors at high frequency excitations (Torrents et
al, 2001). This ‘dual cusp’ behavior is shown in Figure 2.3.
The fiber orientation is determined by the location of the high frequency cusp on the Nyquist plot. When fibers are aligned parallel to the direction of the electric field the dual cusp behavior is very pronounced. However, as the orientation changes the high frequency cusp approaches the low frequency cusp until the two are equal when the fibers are perpendicular to the field. Therefore, by looking at the distance between the low and high frequency cusps, the orientation of the fibers relative to the field direction can be determined. This method can potentially provide a more detailed look at the orientation of the fibers than can be found using the electrical resistivity method.

By placing fibers by hand in several different configurations, Woo et al (2004) were able to investigate the accuracy of the AC-IS method for determination of fiber orientation. The authors found that the fiber orientations determined through the AC-IS method agreed very well with the actual orientations, and that the method was able to detect very small changes in fiber orientation. Other research conducted using AC-IS on concrete reinforced with steel fibers, as well as plant fibers, also showed that AC-IS can

*Figure 2.3. Nyquist plot used in AC-IS method. (Woo et al, 2004)*

2.3.5 Analytical and Theoretical Methods

In addition to the experimental methods discussed, several researchers have attempted to develop theoretical models to predict the behavior of reinforcing fibers in UHPC. These methods are generally derived based on the behavior of a single fiber in several different situations, and then extended to a larger number of fibers in a group. The aim of these methods is to accurately describe the average fiber orientation based on factors that may impact the fiber orientation, without the need to perform time consuming and costly measurements.

Reinforcing fibers have the greatest impact on strength when they are oriented perpendicular to a cracked plane, and thus bridging the cracks. It follows from this that a large number of fibers bridging a cracked plane will result in a higher strength. Dupont and Vandewalle (2004) developed a theoretical method to predict the number of fibers crossing plane based on previous work by Krenchel (1975). According to Krenchel, the number of fibers in a plane can be determined with Equation 2.1.

\[ n = \alpha \frac{V_f}{A_f} \]  

(2.1)

Where:

\[ n \] = number of fibers per unit area

\[ \alpha \] = orientation coefficient

\[ V_f \] = fiber volume fraction

\[ A_f \] = cross-sectional area of a single fiber
In order to account for the effect of the formwork on the fibers, different orientation coefficients can be calculated for each of the boundary conditions. The boundary conditions considered by the authors include a fiber near a single side of the formwork, a fiber in a corner, and a fiber surrounded only by concrete away from all formwork. Using these orientation factors, an average orientation factor for the entire sample can be calculated using Equation 2.2.

\[
\alpha = \frac{\alpha_1 \times (b - l_f) + \alpha_2 \times ((b - l_f)l_f + (h - l_f)l_f) + \alpha_3 \times l_f^2}{bh}
\] (2.2)

Where:

\(\alpha_i\) = orientation factor in zone \(i\) \((i = 1, 2, 3)\)

\(b\) = sample width

\(h\) = sample height

\(l_f\) = length of a single fiber

This method was used by the authors on data obtained by researchers at K.U. Leuven, Belgium. The results agreed well with the experimental results, with an average ratio of calculated to experimental number of fibers of 1.002 (Dupont & Vandewalle, 2004).

The behavior of the reinforcing fibers in UHPC during pouring is very complex and is affected by many things. To create a complete model that can predict the final fiber orientation, all of the factors that affect the fiber orientation must be included in the model. This type of model was developed by Laranjeira et al (2012). In order to account for the different factors that affect the fiber orientation, orientation numbers were defined for fresh concrete after mixing, concrete after placing into formwork, after dynamic effects such as concrete flow or vibration, and after wall effects from formwork have
taken place. By combining the orientation numbers for the different effects, the orientation number for the hardened state can be calculated. This model was applied to experimental data obtained by previous researchers. The method developed was able to predict the average fiber orientation very well, with a maximum deviation for all cases of 5.3% (Laranjeira et al., 2012).

2.4 Adjacent Box Beam Bridge Connections

Being the component that connects individual box beams together to form a single structural system, the shear key is potentially the most important component in this type of structure. Without a well-designed and constructed connection, the joint can fail leading to reduced load transfer between box beams, resulting in the beams carrying more load than they were designed for (Huckelbridge et al., 1995). Cracking in the shear key can also lead to water infiltration and further reduction of load transfer due to freeze-thaw damage.

While the problem of shear key cracking is well known, little research has been done on the subject. In order to test the susceptibility to cracking, Miller et al. (1999) tested three different shear key configurations. A top partial-depth shear key with a non-shrinking grout and an epoxy grout were tested along with a mid-depth shear key with epoxy grout. They found that the epoxy grout experienced less cracking than the non-shrink grout, and that the mid-depth shear key was more resistant to cracking due to its decreased exposure to temperature changes. Another benefit of the mid-depth shear key was that the opening above the grout could be sealed to reduce liquid exposure in the event that cracking did occur.
A study conducted by Gulyas et al (1995) tested two different types of grouting materials in vertical and longitudinal shear tests and direct tension tests. It was found that the non-shrink grout typically used in box beam shear keys did not perform as well as the Mg-NH$_4$-PO$_4$ mortar that was used for comparison. The non-shrink grout showed lower strengths as well as higher chloride penetration, making it much less effective as a grouting material for this application. A review of adjacent box beam bridges outside the United States found that cracking of the shear keys rarely occurs in Japanese box beam bridges. This lead to a newly proposed design method that combines Japanese and American design philosophies to create a bridge that is much less likely to experience cracking of the shear keys (El-Remaily et al, 1996). This design method combines a larger amount of transverse post tensioning and wider full-depth shear keys to create a much stronger connection between adjacent box girders.

Despite the wide usage of adjacent box beam bridges, there are very few standards for the design of the actual shear key. The only requirements specified in the AASHTO LRFD Bridge Design Specification are that the joint be at least 7 in. deep and be filled with a non-shrinking grout with a compressive strength of 5 ksi (AASHTO, 2010). Other than these requirements, the design of the joint is left to the state transportation departments. Although there is a lack of standards for the design of the shear key, only one research project has been conducted on how the shape of the shear key affects the performance of the joint. Dong et al (2007) performed finite element analysis on three different shear key geometries and compared the resulting stresses. They found that a narrower and deeper shear key resulted in stresses lower than the
tensile strength of the grout, while the shallower and wider geometries exceeded the grout’s tensile strength. These results support previous research that indicates that full depth shear keys are less prone to cracking than partial depth designs.

The lack of research on shear keys, and the number of adjacent box beam bridges built, leaves lots of room for the improvement of the joints in this bridge type. A solution to the problem of shear key cracking could increase the service life of many adjacent box beam bridges and lower the cost of the structure over its lifetime.

2.5 Overview

In this chapter, an overview of UHPC and research previously conducted on it was given. UHPC is an advanced material that exhibits properties that can improve the performance of structures that are built with it. Before that can happen, more information is needed on the performance of the material in large-scale applications. Design procedures must also be developed if UHPC is going to see widespread use. For this reason, more research is needed on specific applications for UHPC to determine the importance of fiber orientation as well as methods to achieve the desired fiber orientations. As civil engineering structures increase in size, advanced materials such as UHPC will be necessary in order to ensure the longevity of the structures and the safety of those that use them.
CHAPTER 3: METHODOLOGY

In this chapter the procedure followed to determine and quantify the fiber orientation within a UHPC shear key will be discussed. This will include the creation of a replica shear key as well as image acquisition and analysis, and analysis of the data obtained from the image analysis step.

3.1 Replicating the Shear Key

In order to investigate the fiber orientation in the shear key, samples must be taken from different locations along the joint. Obtaining these samples from the bridge would reduce the strength of the joint, as well as increase the amount of time required for construction and road closure. To avoid these potential problems, an exact replica of the shear key was created using the concrete mix design used in the actual box beams. A total of four replicas were built so that three different values of dowel bar spacing could be investigated, along with one extra in case one was damaged prior to placing the UHPC.

3.1.1 Shear Key Dimensions and Formwork

The dimensions of the shear key were obtained from shop drawings supplied by the precast contractor. The shear key dimensions are shown in Figure 3.1. Because the focus of this research is on the shear key, creating the entire box beam is unnecessary. For this reason, only the top corners containing the shear key of two adjacent box beams were recreated as shown in Figure 3.2. This significantly reduced the amount of materials needed as well as the weight of the replicas. To allow the flow of UHPC to develop as it would in the bridge joints, the replicas were built with a length of five feet.
As shown in Figure 3.2, a foam insert was used to create the void for the UHPC. This greatly simplified the construction of the concrete formwork needed to create the replica shear keys. Due to the low concrete thickness on the bottom of the forms, two
number four (0.5” diameter) reinforcing bars were placed in the bottom of the forms to increase the strength. Reinforcement was also placed at approximately the mid-height of the forms. The plywood formwork is shown in Figure 3.3 with and without the foam insert in place.

![Formwork with and without foam insert](image)

*Figure 3.3. a) Empty formwork. b) Formwork with foam insert in place.*

To strengthen the bond between the UHPC and the box beams in the bridge, a chemical retarder is sprayed onto the formwork prior to casting the beams. After the bridge beams are removed from the forms, the joint area is pressure washed to expose the aggregate, leaving a rough surface for the UHPC to bond to. To replicate this, the retarder used by the precast manufacturer was applied to the foam inserts approximately twelve hours prior to pouring the concrete. A layer of adhesive was also added between the retarder and the foam to prevent the chemicals from destroying the foam.
3.1.2 Transverse Dowel Bars

In the bridge joints, transverse dowel bars are used to help reinforce the joint as well as aid in load transfer between adjacent beams. The dowel bars are made from a short piece of number four rebar (0.5 in. diameter), 4.75 in. long with one end threaded so they can be attached to the beams. In order to investigate how the fibers interact with the dowel bars, the dowels used in the replica shear keys must be made of a material that is much less dense than steel. If steel were used, the fibers and the dowel bars would be indistinguishable in the CT scan images and very little information about the interaction could be obtained.

To eliminate this problem, a resin typically used for fiberglass was used to make the dowel bars for the replicas. A two part aluminum mold was created from a 7 in. long section of rebar identical to that used for the bridge dowels. The resin was poured into the mold and allowed to harden for approximately 30 minutes before removing the hardened dowel bar. This allowed the dowel bars to retain the surface deformations that are present on the steel dowel bars, while having the low density needed for the CT scanning. The aluminum mold is shown in Figure 3.4 along with one of the resin dowel bars.
To avoid casting the resin dowels into the concrete, holes were created through the concrete so that the dowels could be placed into the shear keys after the foam was removed. To make the holes, the dowel locations were marked on the plywood forms and holes were drilled. Shallow holes were also drilled into the foam in the same locations. Half-inch diameter wood dowels were placed through the hole in the form and into the hole in the foam to keep the dowel level as well as to help hold the foam in place. Similar to strand debonding in prestressed members, the wood dowels were sheathed in a plastic tube so that the concrete did not bond to the dowels, allowing them to be removed after the concrete hardened, leaving a hole for the resin dowel bars. The sheathed dowels can be seen in Figure 3.5.
Figure 3.5. Plastic sheathed dowels used to create holes for resin dowel bars.

The dowel bar layout for the four replicas is shown in Figure 3.6 below. In this figure, the dowel bar spacing is as follows, clockwise from the bottom left: six inch spacing, four inch spacing, twelve inch spacing, and universal spacing.

Figure 3.6. Dowel placement layout for shear key replicas.
3.1.3 Concrete Placement

In order to replicate the conditions present in the actual bridge, the same concrete mix design used in the box beams was used to create the shear key replicas. The mix design, shown in Table 3.1, was obtained from the beam manufacturer and used by a local concrete company to create the mix used in the replicas.

Table 3.1

Concrete Mix Design for Shear Key Replicas

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (lb./yd$^3$)</th>
<th>Volume (ft$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>775.0</td>
<td>3.943</td>
</tr>
<tr>
<td>Water</td>
<td>283.0</td>
<td>4.535</td>
</tr>
<tr>
<td>Coarse Aggregate</td>
<td>1600.0</td>
<td>9.603</td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>1189.0</td>
<td>7.164</td>
</tr>
<tr>
<td>Air Content (%)</td>
<td>6.5</td>
<td>1.755</td>
</tr>
<tr>
<td>Admixtures:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Entrainer (oz.)</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Super Plasticizer (oz.)</td>
<td>99.2</td>
<td></td>
</tr>
</tbody>
</table>

Once all formwork was complete, the forms were moved outside so that the concrete could be poured. Concrete was poured into the forms and vibrated to remove trapped air, and finished as smooth as possible. The forms were then covered in plastic and left to
cure for 24 hours. Figure 3.7 shows the completed forms prior to pouring concrete, while Figure 3.8 shows the forms during the concrete pour as well as after 24 hours of curing.

*Figure 3.7. Complete formwork prior to pouring concrete.*

*Figure 3.8. a) Formwork during concrete pour. b) Formwork after 24 hr. cure time.*

After curing for 24 hours, the foam was removed from the concrete, leaving a void in the shape of the shear key. Once the foam was removed, the void was power
washed to create the exposed aggregate finish. Figure 3.9 shows the concrete after the foam was removed, and after power washing.

![Figure 3.9. a) Shear key replica with foam removed. b) Exposed aggregate after power washing.](image)

3.2 Placement of UHPC in Shear Key Replicas

To fill the shear key replicas with UHPC, they were transported to the bridge construction site prior to the bridge joints being poured. The replicas were prepared to match the conditions present in the bridge as closely as possible. This included covering the top of the joint with plywood, sealing any gaps in the formwork with spray foam, and creating chimneys to aid in the placement of the UHPC. Figure 3.10 shows the four inch spacing replica with the chimney in place just prior to pouring the UHPC.
Once the bridge joints were filled, the remaining UHPC was transported from the mixers to the replicas in wheelbarrows. The replicas were then filled with the assistance of the on-site personnel from Lafarge North America. Figures 3.11 through 3.13 show the UHPC being poured into the replicas. Due to time constraints, an improvised chimney, in the form of a plastic bucket, was used on one of the replicas as shown in Figure 3.12.
Figure 3.11. UHPC placement for four inch dowel spacing replica.

Figure 3.12. UHPC placement for universal dowel spacing replica.
Once filled, the chimneys were covered with plastic to help retain the moisture within the joint as shown in Figure 3.14. The replicas themselves were then covered with plastic to further prevent moisture loss. After approximately nine days of curing, the replicas were transported back to the laboratory where the samples were obtained.
3.3 Sample Preparation

A total of seven samples were taken for analysis from the replicas with 4 in. and 6 in. dowel spacing. As none of the replicas were damaged during transport, dowels were added to the spare replica at 12 in. spacing. The two replicas with 12 in. spacing will be used in future research. Because of the size of the replicas, a core drill was used to obtain the samples rather than attempting to cut the replicas into pieces. The cores were taken using a 1.25 in. diameter core bit so that the samples would be small enough that the CT scans would produce images of adequate quality. Five of the seven samples have diameters of 1.25 in. and depths of 1.25 in., while the two samples that contain dowel bars have a diameter of 1.25 in. and a depth of 1.5 in. to include more fibers around the dowel bars. Figure 3.15 shows the coring drill during the coring process.
The sample locations were chosen so that the fiber orientation could be investigated under different conditions present within the shear key. Samples that included a resin dowel bar were taken from the dowel closest to the center of the replica that they were removed from. This was done so that the influence of the dowel on the fiber orientation, as well as the effect of dowel spacing on fiber orientation could be investigated. To examine how the fibers flow around the dowels, a sample was taken at the level of the dowels and midway between two dowel bars. Samples were also taken immediately before and after a dowel bar from the replica with four-inch dowel spacing. A final sample was taken from the edge of the shear key to determine if the surface interaction had any effect on the fibers. The sample locations are shown in Figure 3.16.

Before drilling a core, a line parallel to the keyway was drawn through the center of the core location. This line was later used as a reference to create a notch in the top of the

Figure 3.15. Coring drill used to obtain samples.
sample so that the orientation of the sample within the replica could be determined. The notch is easily distinguished during image analysis so that the axis parallel to the keyway can be matched to one of the axes in the image analysis program.

*Figure 3.16. Sample locations in shear key replicas.*
3.4 CT Scanning

The CT scanning was done using an eXplore CT 120 X-Ray CT scanner from TriFoil Imaging. The scanner is operated by the Edison Biotechnology Institute and is located in the Konneker Research Center. The scanner is capable of producing pixel resolutions of 25 µm, and has a peak source power of 5 kW. During the scan, the sample remains stationary while the X-Ray source rotates around the sample. The resolution, scan time, and other settings can be changed by defining custom scanning protocols for different applications. Due to the high density of the UHPC and the small size of the fibers, a high power and high resolution scanning protocol is required to produce images of adequate quality. Figure 3.17 shows the CT scanner along with the first six samples prior to scanning.

Figure 3.17. a) CT scanner used for imaging. b) Samples 4A – 4F prior to scanning.
The scan time depends on several factors such as resolution and whether or not a full 360° scan is used. In this experiment, scan times were typically several hours to obtain the highest possible resolution. The images are reconstructed by a computer in real time so that the complete volume image is available immediately after the scan is completed. The volume image is composed of multiple slices that when stacked, make up a 3D representation of the sample that includes the concrete as well as the fibers and any air voids within the sample.

3.5 Image Analysis

In order to measure the orientation of each individual fiber, the fibers in the images must be separated from the concrete matrix that surrounds them. This is done through image segmentation. To perform the image analysis, the Avizo Fire image analysis program was used. This program is designed for material science research and contains powerful image processing features and measurement tools.

3.5.1 Image Segmentation

The image segmentation is the most important step in the process of determining fiber orientation. All of the fibers must be separated from the concrete and they must be separated accurately. Avizo Fire contains several tools to perform segmentation including histogram segmentation, interactive thresholding, and watershed segmentation among others. These tools allow the user to segment images into multiple materials interactively or by specifying values for certain parameters, and the program then segments the images based on these settings.
Due to the small size and large number of fibers, it is not feasible to utilize these tools to automatically segment the images from UHPC samples. Several errors can occur that produce inaccurate segmentation results. The first occurs when two or more fibers are very close together or are touching. When this happens, the program interprets the grouped fibers as a single object. When measurements are performed after the segmentation is completed, the program will measure the group of fibers as a single object rather than measuring each fiber that it contains. This results in highly inaccurate measurement of orientation as well as the number of fibers within the sample. The second error occurs when the intensity of a fiber’s gray values change along its length. The fibers are separated from the concrete based on the brightness value of the grayscale pixels in the images, known as gray values. By defining the gray value of the threshold between fibers and concrete, pixels with gray values above the threshold are added to the Fibers material while pixels with gray values below the threshold remain in the Concrete material. The problem occurs when the gray values of a fiber drop below the threshold due to beam hardening or insufficient X-Ray penetration that results in a darker image. When this happens, the fiber is cut off at the point that the gray value drops below the threshold, and the fiber ends. The remaining portion of this fiber may be added as a separate fiber, or may not be added at all if the entire portion is below the threshold value.

To avoid these problems, the region-growing tool in the Avizo Fire segmentation editor was used to manually segment each individual fiber. This allows each fiber to be separated very accurately by changing the threshold value so that each fiber is selected
entirely before adding it to the Fiber material. The segmentation editor allows connected voxels to be selected in all slices so that a whole fiber can be selected by selecting any part of it in any slice. The selection can then be checked for errors by quickly scrolling through the slices and ensuring that no connecting fibers exist before adding the fiber to the Fibers material. Occasionally, fibers that are very close together will be connected regardless of the selection method. When this occurs, the segmentation editor can be used to remove the voxels from the selection that are connecting the fibers. The unconnected fibers can then be added to the Fibers material. While considerably slower, using this method ensures that all fibers are separated and that the segmentation is as accurate as possible.

3.5.2 Fiber Measurements

Once the segmentation is complete, measurements can be performed on the segmented materials using the XQuant Pack in Avizo Fire. The XQuant Pack contains tools to perform a large number of measurements on images. The image obtained from the CT scan contains information about the voxel size, which allows the program to provide measurement results in tangible units rather than a number of pixels. While the program can perform a very large number of measurements, only a few are needed for determining fiber orientation. For each fiber, the following measurements are performed: 3D length, 3D volume, Theta and Phi orientation angles, and the x, y, and z coordinates of the center of gravity. The volume and length measurements are mainly used to check for any errors that may have occurred during segmentation. By comparing the measured
values to the known values based on actual fiber dimensions, any groups of connected fibers can easily be identified by a length or volume larger than the actual fiber values.

Theta and Phi are the two orientation angles that describe the position of the fiber in spherical coordinates. Phi is the elevation angle between the fiber and the positive z-axis ($0 \leq \Phi \leq 90$) and Theta is the rotation angle around the z-axis ($-180 \leq \Theta \leq 180$) as shown in Figure 3.18. The center of gravity coordinates are not used in determining fiber orientation, but can be used along with the coordinates of a fiber end point to recreate the fibers in a finite element analysis program. This is discussed in detail in section 3.8.

![Figure 3.18. Orientation angles measured in Avizo Fire.](image)

### 3.5.3 Fiber Approximation Module

A benefit of using CT scans to determine fiber orientation is that the fibers can be visualized in 3D, and information about the orientation can be obtained visually. To
simplify the visualization, a fiber approximation module developed for this specific purpose was used. The module was developed by the makers of Avizo Fire (Visualization Sciences Group) to aid in the visualization of small fibers in fiber-reinforced materials. The module takes the measured length, orientation angles, and center of gravity coordinates as inputs, and places a cylinder in the fiber location. The cylinder diameter can be changed manually to match the size of the fibers used in the material. The module can also be used to show individual fibers, or small groups of fibers that may be of interest. By approximating the fibers as cylinders, they can be visualized without the need to generate a surface for the fibers. The large number of fibers would require a very large surface that would be very time consuming to generate and difficult to manipulate.

As the fiber approximation module is not a feature that comes standard in Avizo Fire, it had to be added to the program before it could be used. The module, as obtained from VSG3D, only consisted of the files necessary to assemble the module. The module was compiled using Microsoft Visual Studio 2008, and placed into the correct location within the Avizo Fire directory according to instructions provided by Avizo Fire support staff.

3.6 Data Analysis

The data obtained from the image analysis can be utilized to quantify the average orientation of the fibers in a sample. This can be done in several ways, with some being more accurate than others. Three methods for describing the fiber orientation that have been successfully used by previous researchers were adopted to quantify the fiber
orientation in this experiment. This section will describe the methods used to analyze the fiber data in order to describe the overall orientation.

3.6.1 Orientation Number

The first method utilized to quantify the fiber orientation is through a quantity called the orientation number. The orientation number is defined as the projected length of a fiber in a cross-section onto a plane perpendicular to the cross-section, divided by the fiber length. It is essentially a measure of degree to which a fiber is parallel to a particular axis. An orientation number of 1 corresponds to a fiber that is exactly parallel to the axis of interest, while an orientation number of 0 corresponds to a fiber that is perpendicular to the axis of interest. The orientation number can be calculated using Equation 3.1 (Herrmann & Eik, 2011). The orientation number is typically calculated with respect to the principle tensile direction, but may be calculated with respect to any axis of interest so long as the angle between the fiber projection and the axis can be determined.

\[
\eta_i = \frac{1}{N} \sum_{i=1}^{N} \cos \theta_i
\]  

(3.1)

Where:

\[\eta_i = \text{orientation number with respect to an axis } i\]

\[N = \text{total number of fibers}\]

\[\theta = \text{angle between the fiber projection and the } i \text{ axis (} \in 0, 90)\]

Because the out-of-plane angle is not considered in its calculation, the orientation number is only able to provide a description of the orientation in two dimensions. This results in an incomplete description of fiber orientation, since the fibers are oriented in three dimensions. However, a basic 3D description can be obtained by calculating the
orientation number with respect to the x, y, and z-axes of the sample. By looking at the three orientation numbers, a description of the orientation in three dimensions can be obtained. Because this experimental program is only looking at the fiber orientation, and no mechanical testing was conducted, the orientation numbers were calculated with respect to the three axes of the samples as described above. Because the orientation angles determined with Avizo Fire are in spherical coordinates, they must be transformed to obtain the proper angles between the fibers and the x and y-axes.

To calculate the orientation number, the angles between a fiber and the selected axis must be between 0° and 90°. The elevation angle, φ, obtained from Avizo Fire is already within this range and therefore does not need to be changed. However, the rotation angle θ, is in the range of -180° to +180°. For fibers in the negative portion of this range, the angles are converted to positive angles using Equation 3.2, which results in all fibers having a rotation angle within the range of 0° to 180°.

\[
\theta' = \begin{cases} 
\theta & \text{for } \theta \geq 0^\circ \\
\theta + 180 & \text{for } \theta < 0^\circ 
\end{cases} \tag{3.2}
\]

Where:

\( \theta = \) rotation angle measured in Avizo Fire in degrees (\( \theta \in -180,180 \))

\( \theta' = \) transformed rotation angle in degrees (\( \theta' \in 0,180 \))

Using these transformed angles, the angle between the fibers and the x and y-axes can then be determined. Using simple geometry, the angle between the fibers and the x-axis were determined using Equation 3.3.

\[
\theta_x = \begin{cases} 
\theta' & \text{for } \theta' \leq 90^\circ \\
180 - \theta' & \text{for } 90^\circ < \theta' \leq 180^\circ 
\end{cases} \tag{3.3}
\]
Where:

\[ \theta' = \text{transformed rotation angle calculated using Equation 3.2} \]

\[ \theta_x = \text{angle between fibers and the x-axis of the sample in degrees (} \in 0,90) \]

Similarly, the angle between the fibers and the y-axis are calculated using Equation 3.4.

\[ \theta_y = \begin{cases} 
90 - \theta' & \text{for } \theta' \leq 90^\circ \\
\theta' - 90 & \text{for } 90^\circ < \theta' \leq 180^\circ 
\end{cases} \]

(3.4)

Where:

\[ \theta' = \text{transformed rotation angle calculated using Equation 3.2} \]

\[ \theta_y = \text{angle between fibers and the y-axis of the sample in degrees (} \in 0,90) \]

The calculations of the angles using Equations 3.2 through 3.4 were done in a spreadsheet using conditional statements. Because the angles must be calculated for each individual fiber, this greatly reduced the time required to determine the angles needed.

Once the angles with respect to the x, y, and z-axes were determined, the orientation numbers were then calculated using Equation 3.1. By organizing the data obtained from Avizo Fire in the same way for each sample, the orientation numbers could be quickly calculated by copying the formulas from the first sample into spreadsheets for the other six samples.

3.6.2 Probability Density Function

The second method used to quantify the fiber orientation is through a probability density function (PDF), and probability density histogram. The PDF describes the probability of a fiber having a particular orientation. A simple way to obtain a PDF is by fitting a smooth curve to a probability density histogram. This curve can then be integrated to find the probability that a fiber has an orientation within a specified range.
The probability density histogram can also be used to visually determine the orientations that have the highest probabilities. In this experiment, probability density histograms were created in Microsoft Excel, and curves were fit to the histograms using the curve fitting toolbox in Matlab.

To create the probability density histograms, the histogram tool in Excel was used to find the frequency of measured angles within each bin. This data was then normalized so that the area under the PDF is equal to one. A smoothing spline curve was then fit to the normalized data, and integrated over the range of angles using Matlab. The curve’s smoothing parameter was adjusted until the area under the curve was equal to one, and the histogram and curve were then plotted together as shown in Figure 3.19. Probability density histograms were generated for the $\theta$ and $\phi$ angles for each sample, and can be found in Appendix B.

![Probability density histogram of rotation angle $\theta$ with curve fit to data.](image)

**Figure 3.19.** Probability density histogram of rotation angle $\theta$ with curve fit to data.
3.6.3 Alignment Tensors

The final method used for quantifying fiber orientation is through fiber alignment tensors. The alignment tensor, \( A \), is a second order tensor that is calculated using the orientation data obtained from the image analysis. The average overall fiber orientation in a sample is determined by a quantity known as a director, denoted by \( d \). The director is defined as a unit vector in the direction of the eigenvector corresponding to the largest eigenvalue of \( A \). In order to calculate the alignment tensor, the fiber length and orientation angles measured in Avizo Fire are used to calculate the x, y, and z components of each fiber according to Equations 3.5 through 3.7.

\[

\begin{align*}
    v_x &= L \times \sin \phi \times \cos \theta' \\
    v_y &= L \times \sin \phi \times \sin \theta' \\
    v_z &= L \times \cos \phi
\end{align*}

\]

Where:

- \( v_r \) = the \( r \) component of the fiber component vector, \( v \)
- \( L \) = the fiber length measured in Avizo Fire
- \( \phi \) = fiber elevation angle
- \( \theta' \) = fiber rotation angle

These components make up a vector that describes the orientation of a fiber. A tensor is then calculated for each fiber by calculating the outer product of the fiber component vector, \( v \), as shown in Equation 3.8.
Where:

\[ S_i = v_i \otimes v_i \]  \hspace{1cm} (3.8)

These tensors are then used to calculate the alignment tensor for the entire sample using Equation 3.9 (Suuronen et. al., 2013)

\[ A = \frac{1}{N} \sum_{i=1}^{N} S_i \]  \hspace{1cm} (3.9)

Once the alignment tensor has been calculated, the eigenvalues and eigenvectors are determined by solving the eigenvalue equation, which is given in Equation 3.10. The eigenvector corresponding to the largest eigenvalue is the director, \( d \), which gives the average direction of the fibers in the sample.

\[ (A - DI)V = 0 \]  \hspace{1cm} (3.10)

Where:

\( A \) = alignment tensor calculated using Equation 3.9

\( D \) = matrix containing eigenvalues of \( A \)

\( V \) = matrix containing eigenvectors of \( A \)
\( I = \) identity matrix

To make interpretation of the results of this analysis simpler, rotation and elevation angles \( (\theta, \phi) \) were calculated from the components of the director. The tensor analysis was done using a Matlab program that was written specifically for this purpose. The fiber component vectors were created in a spreadsheet, which is then read by the Matlab program, which then calculates and displays the director along with the \( \theta \) and \( \phi \) angles. The Matlab code used in this analysis can be found in Appendix A.1.

It should also be stated that there is an important difference between the alignment tensor and the orientation number. It is possible to have different orientations with the same orientation numbers. This is due to the fact that the alignment director provides the average orientation, while the orientation number is the average of the fiber length parallel to a particular axis. To better illustrate this, an example is provided below. Figure 3.20 shows two groups of five fibers, oriented at 45° and 135°. The orientation numbers for the x and y-axes for this orientation are both equal to 0.707, and the rotation angle of the alignment director is equal to 90°. Figure 3.21 shows a single group of ten fibers oriented at 45°. For this fiber orientation, the orientation numbers for the x and y-axes are also equal to 0.707, while the rotation angle of the alignment director is equal to 45°. This illustrates that although the orientation number for a particular axis may be high, the average overall orientation may not have a component in that axis’ direction.
In order to evaluate the experimental method, two small UHPC cubes were analyzed using the methods described in sections 3.4 through 3.6. The cubes were cut from a small rectangular beam that was created by cutting along the corner of a large block of UHPC. The cubes were cut from the interior edge of the beam; one at the end,
and the other at the midpoint. The beam and the UHPC block are shown in Figure 3.22. Both cubes are approximately 1.5” x 1.5” x 1.25”. These dimensions were chosen based on the fiber size, and to match the capabilities of the CT scanner. These dimensions are several times the fiber length, while also being small enough that the X-Rays are able to penetrate well enough to result in good image quality.

CT scans were then performed on the two cubes. Images from the CT scans of the two samples are shown in Figure 3.23. The center sample was scanned at much higher X-Ray energy, which results in a much clearer image. The images were then exported to Avizo Fire for the fiber analysis. A de-blurring filter was applied to the images to reduce noise and sharpen the edges of the fibers. Using the segmentation editor and the region-growing tool, the fibers were separated from the concrete matrix and added to a material labeled Fibers. In order to catch any errors in the segmentation, measurements were performed on the Fibers material periodically. By comparing the volume and length measurements to the values based on actual fiber dimensions, any errors could easily be identified and fixed.
Figure 3.22. UHPC beam used to retrieve samples for testing of experimental method. Arrow shows the edge used to create samples.

Figure 3.23. a) CT image of end sample. B) CT image of center sample.

When a fiber was found to have a volume or length larger than an actual fiber, it was isolated using the fiber approximation module. By looking at slices that intersect the cylinder of the approximation module, the incorrect fiber could be located, and the error fixed. Once all fibers were segmented and all errors were eliminated, the measurement
data was exported to an Excel spreadsheet for analysis. Once in Excel, the rotation angles were transformed as described in Section 3.5.1. The orientation numbers were then calculated for each direction within the data spreadsheet using Equation 3.1. Table 3.2 shows the orientation numbers for the two test cubes.

Table 3.2

Orientation Numbers for Test Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\eta_x$</th>
<th>$\eta_y$</th>
<th>$\eta_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>End Sample</td>
<td>0.490</td>
<td>0.753</td>
<td>0.157</td>
</tr>
<tr>
<td>Center Sample</td>
<td>0.450</td>
<td>0.813</td>
<td>0.597</td>
</tr>
</tbody>
</table>

From the orientation numbers, it can be seen that in the end sample, the fibers are aligned more parallel to the y-axis, and mostly perpendicular to the z-axis. This corresponds to the vast majority of fibers lying within the x-y plane, and being more parallel to the y-axis than the x-axis. This can be verified visually using the fiber approximation module in Avizo Fire. Figure 3.24 shows the fiber approximation of the end sample. It can be seen that most of the fibers lie in the x-y plane, and mostly parallel to the y-axis as indicated by the orientation numbers. The same can be done for the middle sample. Figure 3.25 shows the fibers are oriented much more randomly in this sample, which agrees with the higher orientation numbers in each direction.
Figure 3.24. Fiber approximation of end sample.

Figure 3.25. Fiber approximation of center sample.

The probability density histograms and PDFs were created using Excel and Matlab as described in Section 3.6.2. Figures 3.26 through 3.29 show the probability density histograms of the two orientation angles for the end and center cubes.
Figure 3.26. Probability density histogram for end sample rotation angle.

Figure 3.27. Probability density histogram for end sample elevation angle.
Figures 3.26 and 3.27 show that the highest probabilities for the $\theta$ and $\phi$ angles are around $95^\circ$, and $84^\circ$ respectively. It can also be seen that the probabilities for the rotation angle are distributed much wider than those for the elevation angle. This
indicates that many more different rotation angles exist in this sample than elevation angles. Figures 3.28 and 3.29 show similar results for the center sample. To calculate the alignment tensors, the Matlab code in Appendix A.1 was used. The x, y and z components of each fiber were calculated according to Equations 3.5 through 3.7, and the Matlab program was then used to calculate the tensors, directors, and the $\theta$ and $\phi$ angles for the directors. Table 3.3 shows the director in terms of the components of the unit vector, as well as in terms of the two orientation angles.

Table 3.3

*Directors Showing Average Fiber Orientation for Test Samples*

<table>
<thead>
<tr>
<th>Sample</th>
<th>$d[x,y,z]$</th>
<th>$d(\theta,\phi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>End Sample</td>
<td>[-0.0238,0.9852,0.1696]</td>
<td>(91.39,80.23)</td>
</tr>
<tr>
<td>Center Sample</td>
<td>[-0.1863,0.7152,0.6737]</td>
<td>(104.60,47.65)</td>
</tr>
</tbody>
</table>

To more easily show the results of the tensor analysis, polar plots of the directors were created. In these plots, the director is displayed as an arrow pointing in the direction of the rotation angle, $\theta$, and the length of the arrow corresponds to the elevation angle, $\phi$. Plots of the directors for the two test samples are shown in Figure 3.30.
Figure 3.30. a) Director plot for end sample. b) Director plot for center sample.

The director for the end test sample indicates that the average fiber orientation is approximately parallel to the y-axis, and mostly within the x-y plane which agrees well with the orientation numbers, as well as the PDFs. Again, this can be verified visually using the fiber approximation from Avizo Fire in Figure 3.24 which shows that the majority of the fibers are aligned in the y-direction and are approximately perpendicular to the z-axis. Similar results were obtained for the center sample, with all three analyses indicating that the fibers are more randomly oriented, with an average orientation approximately parallel to the y-axis and much more vertical than the end sample.

The results from the two test samples indicate that the methods used in this experiment to determine the fiber orientation in samples of UHPC work well. The image analysis is able to successfully separate the fibers from the surrounding concrete and perform accurate measurements on each individual fiber to determine the orientation. The overall orientation can then be determined in several different ways and compared to
ensure the accuracy of the results. In addition, the number of fibers per unit volume can be calculated for each sample as well as the fiber volume percentage to determine if any of the areas examined contain a disproportionate number of fibers.

3.8 Data Use for Finite Element Analysis

In addition to characterizing the fiber orientation, the data obtained from the image analysis can also be used to re-create the exact fiber orientation and distribution from a sample for FEA. This could be done in several ways depending on the FEA program being used. This method was developed for use with the Abaqus CAE program. Custom scripts written for Abaqus using the Python programming language can be used to create the fibers from the image analysis data. However, as FEA was not a large part of this experiment, a simpler, albeit slightly more time consuming process was developed using Matlab and AutoCAD.

Repetitive tasks can be automated in AutoCAD using simple scripts. In these scripts, each line contains the commands needed to perform a particular task. AutoCAD reads each line of the script and performs the commands on that line, and moves on to the next task when it reaches the end of the line. This functionality was used to draw each fiber as a cylinder using the data obtained from the image analysis (similar to the fiber approximation module in Avizo Fire). In order to do this, an additional measurement is needed from the image analysis called ‘FirstPoint’. This measurement obtains the x, y, and z coordinates of the first point that the program encounters for each fiber, which corresponds to one of the fiber end points. Using these coordinates along with the
coordinates of the fiber’s center of gravity, the coordinates of the fiber’s other end point can be calculated using Equation 3.11.

\[
\begin{bmatrix}
    x_2 \\
    y_2 \\
    z_2
\end{bmatrix}_i = 2 \begin{bmatrix}
    x_{cg} \\
    y_{cg} \\
    z_{cg}
\end{bmatrix}_i - \begin{bmatrix}
    x_1 \\
    y_1 \\
    z_1
\end{bmatrix}_i
\] 

(3.11)

Where:

\[
\begin{bmatrix}
    x_2 \\
    y_2 \\
    z_2
\end{bmatrix}_i = \text{vector containing coordinates of 2}^{\text{nd}} \text{ end point of the } i^{\text{th}} \text{ fiber}
\]

\[
\begin{bmatrix}
    x_{cg} \\
    y_{cg} \\
    z_{cg}
\end{bmatrix}_i = \text{vector containing coordinates of the center of gravity of the } i^{\text{th}} \text{ fiber}
\]

\[
\begin{bmatrix}
    x_1 \\
    y_1 \\
    z_1
\end{bmatrix}_i = \text{vector containing coordinates of 1}^{\text{st}} \text{ endpoint from Avizo Fire}
\]

Equation 3.11 was derived based on Figure 3.31 and the following equation, modified accordingly to calculate the y and z coordinates:

\[
\begin{align*}
    x_{cg} - x_1 &= L/2 \cos \theta \\
    x_2 - x_{cg} &= L/2 \cos \theta \\
    \therefore x_{cg} - x_1 &= x_2 - x_{cg} \rightarrow x_2 &= 2x_{cg} - x_1
\end{align*}
\]
Matlab was used to create a program that reads the fiber data from an Excel spreadsheet, and then calculates the second endpoint using Equation 3.11. The program then creates a script file that contains the coordinates of the endpoints along with the correct formatting for use in AutoCAD. This Matlab program can be found in Appendix A.2. After the script is created it can be run in AutoCAD, which results in the fibers being drawn as cylinders with their correct position and orientation as shown in Figure 3.32.
Once the fibers have been re-created in AutoCAD, the file can then be saved in ACIS format for use in Abaqus. The file can then be imported to Abaqus where the group of fibers can be created as a single part, or individual parts for each fiber. This method can also be used to control fiber orientation by inputting the coordinates of the endpoints manually and then running the Matlab program. It should be noted that this method assumes that each fiber is straight and not deformed in any way, which is not always the case. In cases where the fiber is bent, a straight cylinder oriented in the average fiber orientation will be drawn.

This method makes it possible to easily perform FEA on UHPC or other fiber-reinforced materials utilizing the exact fiber orientation and locations. Analytical results can be compared to physical test results to ascertain the accuracy of the model, and calibrate it to fit the actual material behavior if necessary. Once analytical models are developed that accurately simulate the behavior of the material, the models can be utilized to aid in the design of full-scale objects or help develop design methodologies.
CHAPTER 4: RESULTS AND DISCUSSION

Using the method outlined in the previous chapter, seven samples were analyzed in order to determine the orientation of the fiber reinforcement. In this chapter the results from each sample will be presented and discussed individually, followed by a general discussion of the findings. For reference, Figure 4.1 below shows the locations of the samples with their corresponding labels. The number in the sample label indicates the dowel bar spacing within the shear key replica that the sample was taken from.

![Figure 4.1. Sample locations and labels.](image)

4.1 Sample 4A

As shown in Figure 4.1, sample 4A is located approximately mid-way along the length of the shear key replica with four inch dowel bar spacing. This sample is one of two that contain the resin dowel bar in order to determine how the fibers and dowel bars interact. The fiber approximation generated with Avizo Fire is shown in Figure 4.2.
Figure 4.2. Fiber approximation of sample 4A (flow direction is right to left).

Orientation numbers calculated for sample 4A are given in Table 4.1 below, along with the number of fibers found in the sample. The y-axis corresponds to the longitudinal axis of the shear key replicas, while the x-axis is parallel to the dowel bars, and the z-axis is the vertical axis through the shear key. The orientation numbers indicate that the fibers in this sample are aligned more in the direction of flow, than perpendicular to the flow direction. This is consistent with Figure 4.2, which shows that the majority of fibers are aligned with the direction of flow, with changing vertical angles as they are forced over the dowel bar. The orientation numbers also show that the fiber alignment is proportioned similarly with respect to the vertical and horizontal planes.
Table 4.1

*Orientation Numbers for Sample 4A*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>N</th>
<th>$\eta_x$</th>
<th>$\eta_y$</th>
<th>$\eta_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4A</td>
<td>1923</td>
<td>0.467</td>
<td>0.781</td>
<td>0.570</td>
</tr>
</tbody>
</table>

Table 4.2 shows the results of the alignment tensor analysis. As described in the previous chapter, the alignment director is a unit vector pointing in the direction of the average fiber orientation. The director is given in vector form, as well as in terms of the rotation and elevation angles $\theta$ and $\phi$ in order to more easily visualize the vector. A plot of the alignment director is also shown in Figure 4.3 below, where the length and direction of the arrow correspond to the elevation and rotation angles respectively. Plots of the alignment director are oriented such that the vertical and horizontal axes are in the direction of flow, and perpendicular to the direction of flow of the UHPC respectively.

Table 4.2

*Alignment Director in Vector and Angle Forms for Sample 4A*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$d[x,y,z]$</th>
<th>$d(\theta,\phi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4A</td>
<td>[0.0740,0.6917,0.7183]</td>
<td>(83.89,44.08)</td>
</tr>
</tbody>
</table>
Figure 4.3 shows that the overall average fiber direction is almost parallel to the direction of flow, but with an orientation relative to the vertical axis of just under 45°. This can be seen in Figure 4.2, which shows that most fibers are inclined at an angle close to 45° due to the UHPC flowing over the dowel bar.

Probability density histograms, with the probability density function overlaid, for the rotation and elevation angles are shown in Figures 4.4 and 4.5 respectively. These figures were generated in the same manner as described in the previous chapter. Figure 4.4 shows that the most probable rotation angle is around 85°. Similarly, Figure 4.5 shows that the most probable elevation angle is around 45°, with a second peak in the distribution at 90°. These results are consistent with Figure 4.2.
One of the main goals of this experiment was to determine how the fibers interact with the dowel bars. Figure 4.6 is a CT image showing the axis parallel to the axis of the dowel bar, with the flow direction being right to left. The right side of this image shows that the fibers on this side of the dowel bar are much closer together than in other parts of
the sample. This indicates that fibers are building up on the dowel bar as the UHPC flows around it. Also visible in Figure 4.6 is an area around the bottom of the dowel bar (circled in white) that contains a very low number of fibers. This is likely due to the build-up of fibers on the front side forcing other fibers farther down under the dowel, leaving this area relatively free of fibers. The dashed line in Figure 4.6 indicates that the longest dimension of this area is equal to approximately 1.5 times the bar diameter. This fiber distribution can also be observed in Figure 4.2.

Figure 4.6. CT Image showing disruption of flow caused by dowel bar.

A CT image taken perpendicular to the dowel bar is shown in Figure 4.7. It can be seen in this image that air bubbles have formed on the bottom of the dowel bar (circled in white). While air bubbles are routinely found throughout the UHPC, it appears that there is a larger concentration of air voids located on the bottom side of the dowel bar.
4.2 Sample 4B

Sample 4B was located directly below sample 4A in order to examine the fiber orientation in an area with no obstacles interfering with the flow of the UHPC. Due to technical issues with the fiber measurements, the fiber segmentation for this sample was performed in a newer version of Avizo Fire. Because of this, a fiber approximation could not be generated for this sample. The results of the orientation number and tensor analyses are shown in Tables 4.3 and 4.4 respectively.

Figure 4.7. Image showing buildup of air on bottom of dowel bar in sample 4A.
Table 4.3

*Orientation Numbers for Sample 4B*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>N</th>
<th>(\eta_x)</th>
<th>(\eta_y)</th>
<th>(\eta_z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4B</td>
<td>1996</td>
<td>0.379</td>
<td>0.854</td>
<td>0.135</td>
</tr>
</tbody>
</table>

Table 4.4

*Alignment Director in Vector and Angle Forms for Sample 4B*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>(d[x,y,z])</th>
<th>(d(\theta,\phi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>4B</td>
<td>[0.0106,0.9509,0.3094]</td>
<td>(89.36,71.97)</td>
</tr>
</tbody>
</table>

The orientation numbers indicate that the fibers in this sample are oriented mostly in the direction of flow of the UHPC, with the low value of \(\eta_z\) indicating that there are very few fibers oriented in the vertical direction. This is confirmed by the values of \(\theta\) and \(\phi\) in the alignment director, which show that the average rotation and elevation angles are close to 90°, that is, most fibers are parallel to the direction of flow. The director plot for 4B is shown in Figure 4.8, while Figures 4.9 and 4.10 show the probability density histograms for the \(\theta\) and \(\phi\) angles respectively. From Figures 4.9 and 4.10, it can be seen that the highest probabilities occur around 90° for both orientation angles, again demonstrating that most fibers are aligned parallel to the direction of flow.
Figure 4.8. Director plot for sample 4B.

Figure 4.9. Probability density histogram for sample 4B rotation angle.
Figure 4.10. Probability density histogram and PDF for sample 4B elevation angle.

A view of sample 4B, perpendicular to the flow direction, is shown in Figure 4.11 below. As this image shows, fibers that are more inclined are mainly located in the top portion of the sample, which is closest to the dowel bar. This suggests that the dowel bar may be affecting the orientation of a portion of the fibers in sample 4B.
Figure 4.11. Image of sample 4B showing angled fibers located near top of the sample.

4.3 Sample 4C

Sample 4C was located at the midpoint between two dowel bars as indicated in Figure 4.1. Because of how the UHPC flows into the joint and the lack of obstacles below the dowel bars, it was assumed that the dowel bars would have the largest effect on fiber orientation at the height of the dowel bars throughout the joint. For this reason, 4C was cut from the core at the same height as the dowel bar, which can be seen in Figure 3.16 in the previous chapter. Figure 4.12 below shows the fiber approximation for this sample, with the flow direction indicated by the arrow.
The orientation numbers are given in Table 4.5, and indicate that the fibers in sample 4C are oriented mainly in the direction of flow. This can be seen in Figure 4.12, which shows that most fibers are oriented in the flow direction, with some fibers having varying orientations with respect to the vertical axis.

Table 4.5

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>N</th>
<th>$\eta_x$</th>
<th>$\eta_y$</th>
<th>$\eta_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4C</td>
<td>1734</td>
<td>0.327</td>
<td>0.890</td>
<td>0.357</td>
</tr>
</tbody>
</table>

Table 4.6 gives the alignment director, while Figure 4.13 shows the director plot. The average rotation angle shown in Figure 4.13 is approximately in the direction of
flow, with a fairly large elevation angle. This can also be seen in Figure 4.12, which shows that while most fibers are aligned with the flow direction, the fibers in the middle of the sample are more randomly oriented with respect to the vertical axis. This can be attributed to the dowel bar, which forces the fibers to rotate as the flow moves over the dowel, and mixing of the fibers immediately downstream.

Table 4.6

*Alignment Director in Vector and Angle forms for Sample 4C*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$d[x,y,z]$</th>
<th>$d(\theta,\phi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4C</td>
<td>[-0.1932,0.8890,0.4152]</td>
<td>(102.26,65.47)</td>
</tr>
</tbody>
</table>

*Figure 4.13.* Director plot for sample 4C.
Probability density histograms are shown in Figures 4.14 and 4.15. It can be seen from Figure 4.14 that the peak for the rotation angle is around 100°, and the histogram is much narrower than in the previous samples. This means that more fibers are aligned with the flow direction than perpendicular to the flow direction (direction of the dowel bars). Figure 4.15 shows that while most of the fibers are lying closer to the horizontal plane, there are a larger number of fibers oriented closer to the vertical plane. This is consistent with the fiber distribution shown in Figure 4.12.

*Figure 4.14. Probability density histogram for sample 4C rotation angle.*
4.4 Sample 4D

Of the seven samples analyzed, 4D is the only one that was not taken from the center of the shear key. This sample was taken from the wall of the shear key in order to examine the effects of the shear key walls on the fiber orientation. Figure 4.16 shows the fiber approximation for this sample, with the flow direction indicated by the arrow. Orientation numbers are shown in Table 4.7, which indicate that the fibers are aligned almost exclusively in the direction of flow, with very few oriented perpendicular to the flow direction. Table 4.7 also shows that most of the fibers are oriented closer to the vertical axis. This is likely due to the UHPC flowing in the vertical direction, in addition to the longitudinal direction. This orientation can be seen in Figure 4.16, which shows that most fibers are aligned parallel to the direction of flow, with small angles relative to the vertical axis.
Figure 4.16. Fiber approximation for sample 4D (arrow indicates flow direction).

Table 4.7

*Orientation Numbers for Sample 4D*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>N</th>
<th>$\eta_x$</th>
<th>$\eta_y$</th>
<th>$\eta_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4D</td>
<td>900</td>
<td>0.253</td>
<td>0.914</td>
<td>0.597</td>
</tr>
</tbody>
</table>

The alignment director is given in Table 4.8 below, while the plot of the director is shown in Figure 4.17. Like the orientation numbers, the alignment director shows that the overall fiber orientation is almost parallel to the direction of flow, with a vertical angle of approximately 45°, which can also be observed in Figure 4.16.
Table 4.8

Alignment Director in Vector and Angle Forms for Sample 4D

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>(d[x,y,z])</th>
<th>((\theta,\phi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>4D</td>
<td>[0.0616,0.7030,0.7085]</td>
<td>(84.99,44.89)</td>
</tr>
</tbody>
</table>

Figure 4.17. Director plot for sample 4D.

Probability density histograms are shown below in Figures 4.18 and 4.19. Figure 4.18 shows that the peak for the rotation angle is around 85°, and is very narrow. This indicates that there are more fibers parallel to the direction of flow, than there are fibers perpendicular to the direction of flow. It can be seen from Figure 4.19 that there is no distinct peak for the elevation angles. This means that the fibers are more randomly oriented with respect to the vertical axis. This is consistent with the orientation number for the z-axis, which is very close to the value for a random orientation of \(\eta_z=0.5\), and
also with Figure 4.16, which shows that various elevation angles are present throughout the sample.

Figure 4.18. Probability density histogram for sample 4D rotation angle.

Figure 4.19. Probability density histogram for sample 4D elevation angle.
As noted in chapter two, the majority of previous research conducted on UHPC has found that the walls of the formwork have a large effect on the orientation of the fibers. The very low number of fibers oriented perpendicular to the direction of flow shows that these wall effects are also present in the shear key. This also means that the exposed aggregate surface does not have an effect on the orientation of the fibers.

4.5 Sample 4E

Sample 4E was located immediately adjacent, on the upstream side, to one of the dowel bars. Figure 4.20 shows the fiber approximation for sample 4E, with the dashed lines indicating the approximate location of the dowel bar with respect to the sample, and the arrow indicating the direction of flow.

Figure 4.20. Fiber approximation for sample 4E.
The orientation numbers given in Table 4.9 indicate that the fibers are generally oriented in the direction of flow, with elevation angles slightly closer to the vertical axis. This can be seen in Figure 4.20, which shows that most fibers are oriented in the direction of flow, with some fibers oriented closer to the vertical axis. This change in vertical orientation from left to right in Figure 4.20 can be attributed to the dowel bar that is located immediately to the right of the sample, which causes the fibers to change directions as they flow around the dowel bar.

Table 4.9

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>N</th>
<th>$\eta_x$</th>
<th>$\eta_y$</th>
<th>$\eta_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4E</td>
<td>1835</td>
<td>0.396</td>
<td>0.834</td>
<td>0.549</td>
</tr>
</tbody>
</table>

Results of the alignment tensor analysis are given in Table 4.10, and the plot of the alignment director is shown in Figure 4.21. It can be seen from Table 4.10 and Figure 4.21 that the fibers in this sample are aligned mainly in the flow direction, with an angle of approximately 40° relative to the vertical axis. This orientation is very similar to that observed in sample 4A, which included a dowel bar in the sample, and can be seen in Figure 4.20, which shows that the majority of fibers are aligned in the flow direction, with most fibers more vertically oriented.
Table 4.10

*Alignment Director in Vector and Angle Forms for Sample 4E*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>d[x,y,z]</th>
<th>d(θ,φ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4E</td>
<td>[0.0471,0.6922,0.7202]</td>
<td>(86.12,43.93)</td>
</tr>
</tbody>
</table>

*Figure 4.21.* Director plot for sample 4E.

Figures 4.22 and 4.23 below show the probability density histograms for sample 4E. Figure 4.22 reveals that the rotation angle peak is located around 80°, and indicates that there are more fibers aligned parallel to the flow direction than perpendicular to the flow direction. Figure 4.22 shows that most fibers have elevation angles greater than 22°, with no distinct peak in the distribution. This is consistent with Figure 4.20, which shows that most fibers are aligned in the flow direction, with varying elevation angles.
4.6 Sample 4F

Sample 4F was located on the opposite side of the dowel bar from sample 4E, as indicated in Figure 4.1. The fiber approximation is shown in Figure 4.24, with the
approximate location of the dowel bar shown by the dashed lines, and the flow direction indicated by the arrow. Table 4.11 gives the orientation numbers, which show that most fibers are aligned parallel to the flow direction, with elevation angles closer to the horizontal plane than to the vertical axis.

Table 4.11

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>N</th>
<th>ηx</th>
<th>ηy</th>
<th>ηz</th>
</tr>
</thead>
<tbody>
<tr>
<td>4F</td>
<td>1810</td>
<td>0.402</td>
<td>0.853</td>
<td>0.432</td>
</tr>
</tbody>
</table>

Table 4.12 and Figure 4.25 respectively, give the results of the tensor analysis, and show the plot of the alignment director. Figure 4.25 shows that the overall fiber
orientation is almost exactly parallel to the direction of flow, with a fairly large elevation angle. This is consistent with Figure 4.24, which shows that most fibers are aligned in the direction of flow, and are closer to the horizontal plane.

Table 4.12

*Alignment Director in Vector and Angle Forms for Sample 4F*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>d[x,y,z]</th>
<th>d(θ,φ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4F</td>
<td>[0.0099,0.8567,0.5158]</td>
<td>(89.34,58.95)</td>
</tr>
</tbody>
</table>

*Figure 4.25.* Director plot for sample 4F.

Probability density histograms are shown in Figures 4.26 and 4.27 below. It can be seen from Figure 4.26 that the peak for the rotation angle is very wide, indicating that the fibers are not aligned as closely to the flow direction as in previous samples. Figure
4.26 shows that the elevation angle peak is also very wide, indicating that above 45°, many elevation angles are present in the sample. These results are consistent with Figure 4.24, which shows most fibers generally oriented in the flow direction, with varying elevation angles that are closer to the horizontal plane.

Figure 4.26. Probability density histogram for sample 4F rotation angle.

Figure 4.27. Probability density histogram for sample 4F elevation angle.
4.7 Sample 6A

Due to technical problems with the CT scanner, sample 6A is the only sample analyzed from the shear key replica with six inch dowel bar spacing. Like sample 4A, this sample also contains a dowel bar. Figure 4.27 shows the fiber approximation for sample 6A, with the flow direction indicated by the arrow.

![Figure 4.27. Fiber approximation for sample 6A.](image)

Table 4.13 gives the orientation numbers, which indicate that the fibers are aligned mainly in the flow direction, with elevation angles that are slightly closer to the horizontal plane. This is consistent with Figure 4.28, which shows that most fibers are aligned in the direction of flow, with changing orientations with respect to the vertical axis as the fibers flow around the dowel bar.
Table 4.13

*Orientation Numbers for Sample 6A*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>N</th>
<th>$\eta_x$</th>
<th>$\eta_y$</th>
<th>$\eta_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6A</td>
<td>1626</td>
<td>0.479</td>
<td>0.760</td>
<td>0.441</td>
</tr>
</tbody>
</table>

The alignment director is given in Table 4.14, and plotted in Figure 4.29. The alignment director also indicates that the fibers are aligned parallel to the direction of flow, with the value of $\phi$ indicating that the fibers are slightly closer to the horizontal plane than to the vertical axis.

Table 4.14

*Alignment Director in Vector and Angle Forms for Sample 6A*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$d[x,y,z]$</th>
<th>$d(\theta,\phi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6A</td>
<td>[-0.1132,0.7699,0.6281]</td>
<td>(98.37,51.09)</td>
</tr>
</tbody>
</table>
Probability density histograms are shown in Figures 4.30 and 4.31 below. Figure 4.30 shows that the main peak for the rotation angle is located at 90°, with additional peaks at 140°, and 170°. From Figure 4.31, it can be see that the majority of fibers have elevation angles greater than 36°, again, indicating that the fiber alignment in the vertical direction is mainly in the direction of flow. This is consistent with the distribution observed in Figure 4.28.
Figure 4.30. Probability density histogram for sample 6A rotation angle.

Figure 4.31. Probability density histogram for sample 6A elevation angle.

This sample also contains an area on the downstream side of the dowel bar that has a very low number of fibers. Figure 4.32 shows this area outlined in white, with the dashed line indicating the longest dimension of the area, which is equal to approximately
1.7 times the bar diameter. Also visible in Figure 4.32, is the build-up of fibers on the upstream side of the dowel bar.

![Image](image_url)

*Figure 4.32. Under-reinforced area in sample 6A.*

The formation of air bubbles on the bottom of the dowel bar was also observed in this sample, which is shown in Figure 4.33. While it cannot be seen in the figure, the number of air bubbles trapped under the dowel bar, as well as the number of air bubbles in general, in this sample is larger than in sample 4A.
4.8 Overall Results

While the previous sections of this chapter have presented and discussed the results for each sample individually, this section will discuss the overall results of all samples. Table 4.15 gives the orientation numbers for all seven samples, while Table 4.16 gives the alignment directors for direct comparison between samples.

Table 4.15

*Orientation Numbers for All Samples*

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>N</th>
<th>$\eta_x$</th>
<th>$\eta_y$</th>
<th>$\eta_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4A</td>
<td>1923</td>
<td>0.467</td>
<td>0.781</td>
<td>0.570</td>
</tr>
<tr>
<td>4B</td>
<td>1996</td>
<td>0.379</td>
<td>0.854</td>
<td>0.135</td>
</tr>
<tr>
<td>4C</td>
<td>1734</td>
<td>0.327</td>
<td>0.890</td>
<td>0.357</td>
</tr>
<tr>
<td>4D</td>
<td>900</td>
<td>0.253</td>
<td>0.914</td>
<td>0.597</td>
</tr>
<tr>
<td>4E</td>
<td>1835</td>
<td>0.396</td>
<td>0.834</td>
<td>0.549</td>
</tr>
<tr>
<td>4F</td>
<td>1810</td>
<td>0.402</td>
<td>0.853</td>
<td>0.432</td>
</tr>
<tr>
<td>6A</td>
<td>1626</td>
<td>0.479</td>
<td>0.760</td>
<td>0.441</td>
</tr>
</tbody>
</table>

Figure 4.33. Buildup of air under dowel bar in sample 6A.
The results shown in Tables 4.15 and 4.16 show that in all samples, the average fiber orientation is generally parallel to the direction of flow, with varying vertical angles. While the vertical angles vary between samples, the majority of the samples have average elevation angles greater than 45°. Two of the samples with average elevation angles less than 45° contain dowel bars, while the third was located along the shear key wall. For the two dowel bar samples the lower elevation angles are caused by the change in direction as the fibers are forced around the dowel bars. The smaller elevation angles in the wall sample are most likely due to the UHPC flowing in the vertical direction as the joint fills, in addition to flowing along the length of the shear key.

Plots of the alignment directors for each sample can be directly compared in Appendix B, while the probability density histograms can be found in Appendix C. Comparing the rotation angle probability density histograms for each sample reveals that while the most probable orientations are similar, the probabilities of a fiber having a
rotation angle perpendicular to the flow direction varies substantially from sample to sample. This variability is also present, although to a lesser extent, in the elevation angles, where all samples have high probabilities of elevation angles greater than 45°, while the probabilities for angles less than 45° vary widely between samples. This variability in both rotation and elevation angles suggests that while most fibers align in the same general direction, the fibers that are not aligned in the fiber direction are more randomly oriented.

As mentioned above, air bubbles were found concentrated on the bottom of the dowel bars in samples 4A and 6A. In order to determine whether these voids are larger than those typically found throughout the UHPC, the mean volume of the voids around the dowel bars were compared to those throughout the non-dowel bar samples. To perform this analysis, air voids throughout the non-dowel bar samples and around the dowel bars were separated in Avizo Fire using the same method used to separate the fibers. Volume measurements were then performed on the separated voids. Figures 4.34 through 4.37 show examples of the separated air bubbles in samples 4B, 4E, 4A, and 6A respectively.
Figure 4.34. Air voids in sample 4B.

Figure 4.35. Air voids in sample 4E.
Figure 4.36. Air voids around dowel bar in sample 4A.

Figure 4.37. Air voids around dowel bar in sample 6A.
To compare the mean void volume, an ANOVA was performed on the volumes using PASW statistics software. Table 4.17 shows the results of the ANOVA, while Table 4.18 shows the results of the Games-Howell post hoc tests conducted in order to directly compare sample means. Because the variances in void volumes were not homogeneous, the F value reported in Table 4.17 is the Welch’s F ratio. This value shows that there is no significant difference between the mean volumes in each sample. The significance values in Table 4.18 indicate whether or not there is a significant difference in the mean volumes of each sample compared to the others, where a value less than 0.05 indicates that there is a significant difference between the two samples. Therefore, from Table 4.18 it can be seen that there is no significant difference between the mean void volumes in any sample.

Table 4.17

ANOVA Results for Mean Void Volume

<table>
<thead>
<tr>
<th></th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Mean Square</th>
<th>F</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Groups</td>
<td>36.111</td>
<td>6</td>
<td>6.019</td>
<td>3.948</td>
<td>0.001</td>
</tr>
<tr>
<td>Within Groups</td>
<td>3241.333</td>
<td>2063</td>
<td>1.571</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3277.444</td>
<td>2069</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.18

Results of ANOVA Post Hoc Tests for Samples 4A – 4D

<table>
<thead>
<tr>
<th>(I) Sample Number</th>
<th>(J) Sample Number</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>(I) Sample Number</th>
<th>(J) Sample Number</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4A</td>
<td>4B</td>
<td>.44087</td>
<td>.23190</td>
<td>.483</td>
<td>4A</td>
<td>4B</td>
<td>-.37101</td>
<td>.23921</td>
<td>.713</td>
</tr>
<tr>
<td>4B</td>
<td>4C</td>
<td>.54207</td>
<td>.22824</td>
<td>.218</td>
<td>4B</td>
<td>4C</td>
<td>.17105</td>
<td>.10075</td>
<td>.618</td>
</tr>
<tr>
<td>4C</td>
<td>4D</td>
<td>.58166</td>
<td>.22438</td>
<td>.138</td>
<td>4C</td>
<td>4D</td>
<td>.21065</td>
<td>.09167</td>
<td>.247</td>
</tr>
<tr>
<td>4D</td>
<td>4E</td>
<td>.37101</td>
<td>.23921</td>
<td>.713</td>
<td>4D</td>
<td>4E</td>
<td>.01284</td>
<td>.10831</td>
<td>1.000</td>
</tr>
<tr>
<td>4E</td>
<td>4F</td>
<td>.38385</td>
<td>.23168</td>
<td>.646</td>
<td>4E</td>
<td>4F</td>
<td>.01284</td>
<td>.10831</td>
<td>1.000</td>
</tr>
<tr>
<td>4F</td>
<td>4F</td>
<td>.35407</td>
<td>.23635</td>
<td>.746</td>
<td>4F</td>
<td>4F</td>
<td>.01284</td>
<td>.10831</td>
<td>1.000</td>
</tr>
</tbody>
</table>

| 6A                | 4B                | -.44087               | .23190     | .483 | 6A                | 4B                | -.38357               | .23168     | .646 |
| 4B                | 4C                | .10120                | .08188     | .880 | 4B                | 4C                | .05701                | .09103     | .996 |
| 4C                | 4D                | .14079                | .07040     | .416 | 4C                | 4D                | .15821                | .08125     | .450 |
| 4D                | 4E                | -.06986               | .10879     | .995 | 4D                | 4E                | .19781                | .06967     | .070 |
| 4E                | 4F                | -.05701               | .09103     | .996 | 4E                | 4F                | -.01284               | .10831     | 1.000 |
| 4F                | 4F                | -.08680               | .10233     | .980 | 4F                | 4F                | -.01284               | .10831     | 1.000 |
| 6A                | 6A                | -.22759               | .08391     | .100 | 6A                | 6A                | -.22759               | .08391     | 1.000 |
While the air voids that are concentrated under the dowel bars are not larger than those found throughout the UHPC, the fact that they are concentrated under the dowels is a potential problem. Because the dowel bars transfer vertical shear forces, air voids trapped under the dowel bars will reduce the area of UHPC that the dowel bars are bearing on, and increase the stresses in the area around the dowels. This could result in weak points in the shear key.
CHAPTER 5: CONCLUSIONS AND FUTURE WORK

In this experiment, seven UHPC samples from different locations in an adjacent box beam bridge shear key were analyzed using a CT scanning method in order to investigate the fiber orientation. Exact replicas of the shear key used in the Sollars Road bridge in Fayette County, OH were built in order to match the conditions present in the actual box beams. The replica shear keys were transported to the construction site and filled with UHPC using the same methods used to fill the joints in the bridge. After curing, the replica shear keys were transported back to the laboratory where the samples were removed using a 1.25 inch diameter diamond core bit. The samples were then scanned using a µCT scanner, and analyzed using specialized image analysis software in order to measure the orientation of the fibers within the UHPC.

The orientation numbers, alignment directors, and probability density histograms all indicate that the majority of fibers are aligned generally parallel to the direction of UHPC flow, with very few fibers aligned perpendicular to the flow direction, for all samples analyzed. This is consistent with past research conducted on UHPC, and can be seen in Figure 5.1, which shows the average fiber direction for all seven samples. The orientation numbers, alignment directors, and density histograms also indicate that in the samples with dowel bars, the sample before a dowel bar, and the wall sample, there are a large number of fibers that are aligned at an angle between the longitudinal axis of the joint and the vertical direction. For the two dowel bar samples this can be attributed to the fibers flowing around the dowel bars as the joint is filled. For the sample before the dowel, this is caused by the fibers encountering the dowel bar and beginning to move
around it. For the wall samples, this is due to the combination of horizontal and vertical flow of the UHPC. This difference in fiber orientation translates to a difference in mechanical properties of the UHPC between these regions with boundaries (i.e. dowel bars or walls) and the regions without boundaries.

Images of the fiber representation in the dowel bar samples show that there are fibers building up on the upstream side of the dowel bars as the UHPC flows around them. This build-up of fibers also coincides with areas on the bottom, and downstream side of the dowel bars that have very few fibers. Research has found that the dowel bars are subjected to tensile forces as the box beams contract laterally due to environmental loadings. It is possible that the build-up of fibers could result in less UHPC bonding to the dowel bars, and additional tensile stresses being transferred to the area with very few
fibers. As this region already has reduced tensile strength, an increase in tensile stresses could result in tensile cracking. Images of the dowel bar samples also showed that there is an accumulation of air voids on the bottom of the dowel bars. This can be attributed to the air bubbles becoming trapped on the dowel bars as they rise through the UHPC. This collection of air bubbles reduces the amount of UHPC that is bonded to the dowel bars, which, as mentioned above, could increase the stress in the UHPC that is bonded to the dowels, which could lead to cracking.

5.1 Recommendations for Further Research

Based on the results of the fiber orientation analysis presented above, there are several recommendations for further research in order to better understand the behavior of the fibers in UHPC bridge connections. This section will briefly discuss these recommendations.

5.1.1 Analysis of Additional Dowel Bar Samples

While the work performed on samples containing dowel bars provides useful insight into the behavior of the fibers around the dowel bars, further research is still needed. This experiment only analyzed a small number of samples containing dowel bars. In order to make more general statements about dowel bar-fiber interactions, a larger number of samples need to be analyzed. In addition, more samples taken from specimens with differing dowel spacing should be analyzed to determine if the spacing of the dowel bars has any effect on the fibers.
5.1.2 Analysis of Samples from UHPC Pour Locations

When filling the bridge joints, UHPC is poured into the shear keys in several locations along the length of the bridge. While the UHPC is not poured at a new location until the flow from the previous location arrives, these points will have UHPC moving in several different directions. Samples from these locations should be analyzed in order to determine whether converging flow directions result in any detrimental fiber orientations.

5.1.3 Analysis of Air Trapped Under Dowel Bars

It was noted above that air bubbles were observed on the bottom of the dowel bars in samples 4A and 6A. In order to determine whether this occurs in all cases, more samples should be investigated for the presence of air on the bottom of the dowel bars. If possible, further analysis should be conducted to determine if these air voids cause a reduction in the performance of the dowel bars.

5.1.4 Finite Element Analysis Considering Fiber Orientation

In order to better understand the behavior of UHPC, finite element analysis should be conducted that includes the different fiber orientations throughout the volume. This could be used to determine whether collection of fibers on transverse reinforcement leads to a change in the strength of the UHPC in these areas.
REFERENCES


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*Experimental Techniques*, 50-55. DOI: 10.1111/j.1747-1567.2009.00420.x


APPENDIX A: MATLAB CODES

A.1 Alignment Tensor Analysis

```matlab
%%% Calculate alignment tensor, director, & create plot %%%
clear all

N=1626; % Number of fibers in the sample

% Create vectors containing fiber components 
M=xlsread('6A Tensor UD.xlsx','E2:G1627');

for i=1:size(M)
    n(i,:)=M(i,:);
end

% Calculate tensor from vectors 
T=cell(3);
for i=1:N
    T{i}=n(i,:)'*n(i,:);
end

% Calculate 2nd order alignment tensor, A, for whole sample 
S=cell(3);
S{1}=T{1};
for i=2:N
    S{i}=S{i-1}+T{i};
end

A=(1/N)*S{N};

% Calculate eigenvalues and eigenvectors of A 
[V D]=eig(A); % V=eigenvectors D=eigenvalues

% Determine macroscopic director, d 
[maxNum, maxIndex]=max(D(:));

% Row & Column number containing largest eigenvalue 
[row, col]=ind2sub(size(D),maxIndex);

d=V(:,col); % Director

% Calculate angles for the director 
```
if d(3)<0;
d(3)=-d(3);
end

% Z component must be positive

phi=acosd(d(3));

% Elevation angle

if d(1)<0 && d(2)<0;
d(1)=-d(1);
d(2)=-d(2);
end

% Restrict to [0,+180]

if d(1)>0 && d(2)<0;
d(1)=-d(1);
d(2)=-d(2);
end

THETA=acosd(d(1)/sind(phi));

% Rotation angle

% Display director and angles %
display(d);
display(THETA);
display(phi);

% Create polar graph of director %

theta_rad=THETA*(pi/180);

% Convert THETA to radians

[x,y]=pol2cart(theta_rad,phi);

% Convert angles to cartesian coord.
polar(360,90);
hold on;
compass(x,y,'r');

% Plot of director

A.2 AutoCAD Script Generator

%%% Generate script to draw fibers in AutoCAD %%%

clear all

% Input Excel filename, range of columns for measurements, & voxel size %

d1=xlsread('Autocad script example.xlsx','A2:C51')*0.0448;
center=xlsread('Autocad script example.xlsx','D2:F51');
for i=1:length(end1)
    end2(i,1:3)=((center(i,1:3)*2)-end1(i,1:3));
end
endpoints=[end1,end2];

% Format and write script file %

% Name script file.
fileID=fopen('EXAMPLE.scr','w');

for i=1:length(endpoints)
    formatSpec='.cylinder %5.4f,%5.4f,%5.4f 0.1 A %5.4f,%5.4f,%5.4f\n';
    fprintf(fileID,formatSpec,endpoints(i,1),endpoints(i,2),endpoints(i,3),endpoints(i,4),endpoints(i,5),endpoints(i,6));
end
fclose(fileID);

%% NOTE %%

% Excel files must be located in MATLAB folder
% Script files save in MATLAB folder
% Turn off object snap in AutoCAD before running script.
APPENDIX B: ALIGNMENT DIRECTOR PLOTS

B.1 Director Plots for Samples 4A and 4B

B.2 Director Plots for Samples 4C and 4D
B.3 Director Plots for Samples 4E, 4F, and 6A
APPENDIX C: PROBABILITY DENSITY HISTOGRAMS

C.1 Samples 4A – 4C
C.2 Samples 4D – 4F
C.3 Sample 6A