Analysis of UHPC Fiber Alignment in Two and Three Dimensions

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Abstract

The quantity and orientation of steel fibers in a structural UHPC element will impact its ability to carry and distribute tensile stresses. UHPC is typically placed as a highly flowable material. As a result, the fibers in UHPC tend to align along the direction of flow, and in undesirable conditions may segregate. Both of these properties can significantly influence fiber alignment and thereby impact the local tensile behavior of the material. Quality assurance and quality control (QA/QC) methods for characterizing the quantity and alignment of fibers in UHPC elements are needed for assessing the impact of the flow properties and placement methods on the structural performance of a UHPC element. Accordingly, two techniques have been independently developed to characterize fiber distribution and alignment in UHPC cores extracted from structural members: (1) three-dimensional imaging of concrete samples by x-ray microtomography and (2) two-dimensional imaging of individual cut surfaces. This paper presents a collaborative research effort in which the fiber quantity and fiber orientation of ten samples of UHPC, extracted from four different full-scale UHPC members, were characterized using both the three-dimensional and two-dimensional imaging techniques. Parallel analyses were performed to quantify the total fiber content and "axial alignment factors" for each sample using each method, and the results were compared. The results indicate that while three-dimensional imaging by x-ray microtomography of fiber alignment provides a comprehensive assessment of fiber alignment, two-dimensional analysis of cut planes can provide a reasonable estimate for use as a QA/QC method or as a tool to investigate or explain UHPC performance, provided that results are appropriately normalized.

Keywords: Fiber alignment, image analysis, computed tomography, quality assurance/quality control (QA/QC)

1. Introduction

Increasingly, ultra-high-performance concrete (UHPC) is being considered as an attractive option for the design of structural members. The high tensile strength and post-cracking ductility of steel-fiber-reinforced UHPC can allow for the reduction of traditional reinforcing steel, provided that the fibers are distributed and oriented in such a way as to be engaged upon initial cracking of the material (Naaman 2017). Fibers oriented perpendicular to tensile stresses will provide little benefit to the composite in terms of tensile performance and ductility, while fibers oriented parallel to the direction of primary tension can greatly enhance the tensile behavior of a UHPC element.

Studies have shown that the distribution and alignment of fibers within a UHPC element strongly depend on the manner in which the element is produced and that this can influence performance (Kang et al. 2011; Wille and Parra-Montesinos 2012; Maya, de la Varga, and Graybeal 2016; Walsh et al. 2018; Wagner and Lawler 2019). In particular, fibers will tend to align along the direction of flow through forms, and consequently, the placement methods and formwork geometry will have a pronounced effect on the orientation and distribution of fibers within a structural UHPC element. As such, the ability to characterize fiber orientation and fiber distribution for samples of structural UHPC may prove critical to efficient utilization of UHPC for structural applications.

2. Background

A straight steel fiber in UHPC can be approximated mathematically by a right circular cylinder. When a right circular cylinder is intersected by a plane, it creates an ellipse on the surface of that plane, as shown in Figure 1. The ellipse is characterized by minor and major axes of lengths a and b, respectively, which are related to the geometry of the fiber and the angle that the fiber intersects the plane. Specifically, the length of the minor axis (a) is equal to the diameter of the fiber, while the ratio of the minor axis to the major axis (a/b) is equal to the cosine of the deviation angle (θ) that the fiber makes with a vector perpendicular to the intersecting plane.

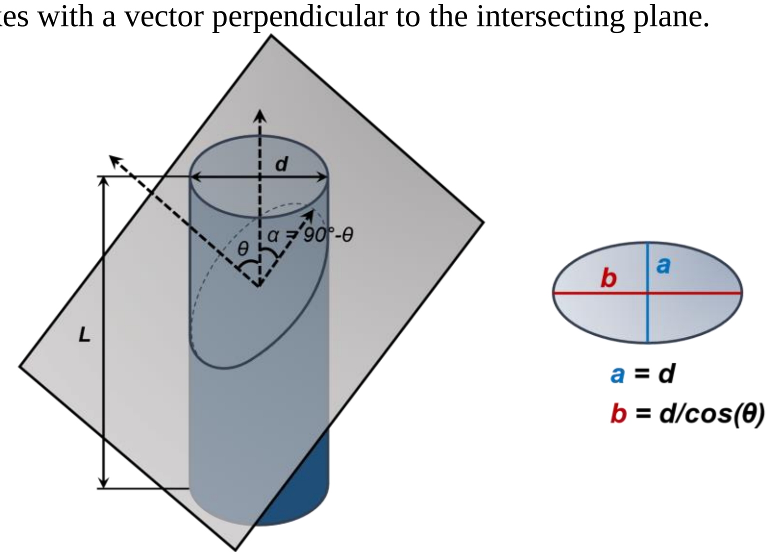


Figure 1. Schematic illustration of an ellipse formed by a plane intersecting a cylinder.

The "axial alignment factor" is a parameter previously developed by the authors (Wagner and Lawler 2019) to describe the contribution of a fiber to tensile resistance in the direction perpendicular to the cut plane. Mathematically, the axial alignment factor can be calculated as the cosine of the deviation angle θ. The axial alignment factor (herein referred to by the parameter "k") is equal to the average of the cosine of θ for each fiber in the region of interest:

$$k = \sum_{i=1}^{N_f} \cos(\theta_i) \,/ N_f \qquad (1)$$

where θ_i is the longitudinal alignment angle of each fiber i and N_f is the total number of fibers in the region of interest. A specimen with all fibers aligned perpendicular to the cut plane ($\theta = 0°$) will have k = 1, while a specimen with all fibers aligned parallel the cut plane ($\theta = 90°$) will have k = 0. It can be shown mathematically that for a perfectly randomized distribution of fibers, the probability of a fiber being oriented at a particular deviation angle will resemble a sine curve due to fewer possible orientations at smaller deviation angles; therefore, the axial alignment factor for a randomized distribution of fibers, $k_{3D,rand}$, in a three-dimensional (3D) space is equal to 1/2. When alignment is characterized based on a two-dimensional (2D) cut plane, the expected axial alignment factor is also related to the probability of the cut plane intersecting the fibers. This probability decreases at greater angles from the reference orientation, and it can be shown that the probability for a perfectly random distribution based on a 2D analysis will resemble a sine-times-cosine curve, and that the axial alignment factor, $k_{2D,rand}$, for the random condition is equal to 2/3.

3. Materials and Methods

Ten core samples were extracted from five different full-scale, precast UHPC members using a 2-inch inner-diameter coring bit. The structural members included two slabs (Cores 31A, 31B, 51A, 51B, 52A, and 52B), a box beam (Cores B2 and B3), an H-pile (Core H1), and an I-beam (Core I1). Elements were produced by multiple precasters using different UHPC mixture designs. Details of the mixture designs and proportions were not provided; however, it was observed that each mixture contained an unknown percentage of steel fibers having a nominal diameter of 0.008 in. (0.20 mm) and a length of 0.5 in. (13 mm).

3.1. Analysis in Three Dimensions using X-Ray Computed Tomography

The cores were first scanned along their longitudinal axis using computed tomography (CT) and analyzed in three dimensions using the software Visual Graphics Studio max (VGStudio max). With this 3D rendering software, individual voxels (3D pixels) were colored based on material density as determined by the CT scanner. To select the correct density threshold to distinguish between concrete and fiber, an iterative process was used by first selecting a threshold and then determining the average fiber diameter using the software. This was adjusted until the software's average fiber diameter aligned with the known fiber diameter of 0.008 in. (0.20 mm). The threshold was then used to determine the fiber volume percent and to perform fiber orientation analyses with respect to multiple reference orientations. Reference orientations were defined as an x-, y-, and z-axis, with the x- and y-axes oriented transverse to the longitudinal axis of the core and the z-axis aligned with the longitudinal axis of the core. During post-processing of samples cut longitudinally for 2D image analysis, the x-axis was oriented perpendicular to the cut plane used for that analysis. The software produced a histogram of voxels versus deviation angle from the reference axis. A 3D axial alignment factor, k_{3D}, was calculated for each reference angle by summing the cosine of the deviation angle multiplied by the number of voxels in that direction and divided by the total number of voxels. The 3D axial alignment factor was then divided by a factor of 1/2 (i.e., $k_{3D,rand}$) to obtain a normalized 3D axial alignment factor k'_{3D}, for which a value greater than 1 indicates greater alignment with the reference orientation than a random arrangement of fibers.

3.2. Analysis in Two Dimensions using Image Analysis

After completion of the CT analysis, one slice was saw-cut longitudinally from eight samples, while two slices were saw-cut transversely from two samples as shown in Table 1. Slices were typically 3/4 in. (19 mm) in thickness. The orientations of the cut surfaces examined in this study were arbitrarily selected and do not necessarily correlate to the direction of flow during element fabrication or to the direction of loading in the element. Each surface of the cut specimen was polished by lapping with successively finer abrasives until the surface was smooth and contained no visual saw-cuts or grooves. To enhance the visual contrast between the steel fibers and the surrounding UHPC mortar, the polished surfaces were treated with a copper sulfate solution, which plated the steel with copper and slightly lightened the surrounding paste. Each polished and plated cross-section was imaged in 24-bit color using a flat-bed scanner at either 4800 or 6400 dpi resolution.

The scanned images were processed using a MATLAB script developed to identify each fiber within the cross-section and to characterize its alignment. Details of the specimen preparation method and MATLAB script are described elsewhere (Wagner and Lawler 2019) but generally consisted of identifying a threshold in the CIELAB color space to visually separate the copper-colored fibers from the predominantly gray/green background image, fitting an ellipse to each fiber detected, and using the geometric properties of the fitted ellipse to calculate the orientation of each fiber relative to an axis perpendicular to the cut face examined (i.e., the angle, θ, as illustrated in Figure 1). The area fraction of fibers was estimated based on the percentage of the image area identified as "fibers" by the thresholding algorithm, while the 2D axial alignment factor, k_{2D}, was calculated as the average of the cosine of the alignment angle θ for all detected fibers.

To obtain a normalized 2D axial alignment factor k'_{2D} that can be directly compared to the normalized 3D alignment factor k'_{3D}, the 2D axial alignment factor was obtained using the following equation:

$$k'_{2D} = 1.5(k_{2D})^2 + 0.5k_{2D} \tag{2}$$

This equation was adopted such that the normalized 2D alignment factor k'_{2D} matches the normalized 3D alignment factor k'_{3D} at points of known correspondence, specifically k'_{2D} is equal to 0 when all fibers are aligned parallel to the cut plane, to 2 when all fibers are aligned perpendicular to the cut plane, and to 1 when the fibers are perfectly randomized (i.e., $k_{2D,rand}$ = 2/3). Like k'_{3D}, a k'_{2D} value greater than 1 indicates greater alignment with the reference orientation perpendicular to the cut plane than a random arrangement of fibers.

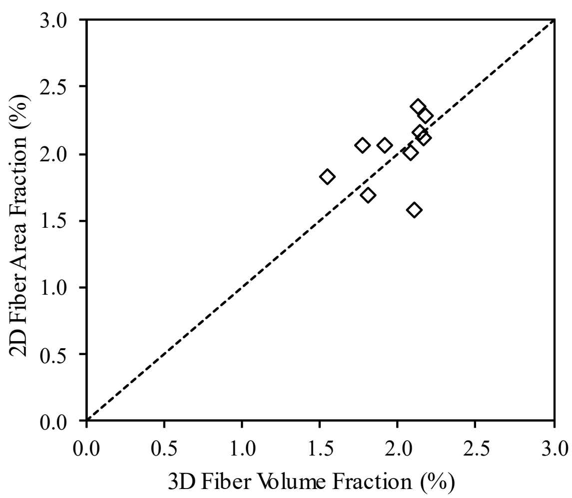
4. Results

Results from the 3D and 2D analyses are presented in Table 1 and plotted in Figure 2. The results from the 3D analyses represent the total volume fraction of fibers and the normalized axial alignment factor (k'_{3D}) over the full volume of each specimen, while results of the 2D analyses represent the area fraction of fibers and normalized axial alignment factor (k'_{2D}) for the analyzed surfaces. Two surfaces were analyzed for cores cut longitudinally (i.e., "x" reference axis) and four surfaces were analyzed for cores cut transversely (i.e., "z" reference axis). Area fraction based on 2D analysis is a one-to-one estimator of volume fraction based on 3D analysis.

For the samples examined, both fiber content and axial alignment factor showed general agreement between the 2D and 3D analyses. There was no clear tendency for the 2D image analysis to over-estimate or under-estimate the fiber content, and the normalized 2D and 3D axial alignment factors appeared to be strongly correlated, though the normalized 2D image analysis did show a slight tendency to under-estimate the axial alignment factor based on 3D analysis for samples with high axial alignment factors (i.e., fibers oriented more perpendicular to the cut plane).

Table 1. Fiber Content and Axial Alignment Factors for 3D and 2D Analyses.

Core ID	Orientation of Cut Surface	Total 2D Surface Area Analyzed, in^2 (cm^2)	Fiber Content, %		Normalized Axial Alignment Factor (k')	
			Volume Fraction of Fibers (3D)	Area Fraction of Fibers (2D)	3D, k'_{3D}	2D, k'_{2D}
31A	Longitudinal	9.4 (60.5)	2.10	1.58	0.60	0.67
31B	Longitudinal	13.0 (83.6)	1.91	2.07	0.62	0.69
51A	Longitudinal	8.2 (53.0)	2.08	2.01	1.31	1.21
51B	Longitudinal	8.7 (56.1)	2.16	2.12	1.06	1.11
52A	Longitudinal	11.0 (70.8)	1.81	1.69	0.94	0.89
52B	Transverse	12.4 (79.7)	2.17	2.29	1.39	1.29
B2	Transverse	12.7 (81.7)	2.14	2.16	0.48	0.54
B3	Longitudinal	14.8 (95.5)	2.13	2.36	1.46	1.31
H1	Longitudinal	8.4 (54.4)	1.77	2.06	1.31	1.23
I1	Longitudinal	15.2 (98.2)	1.54	1.83	0.95	0.97



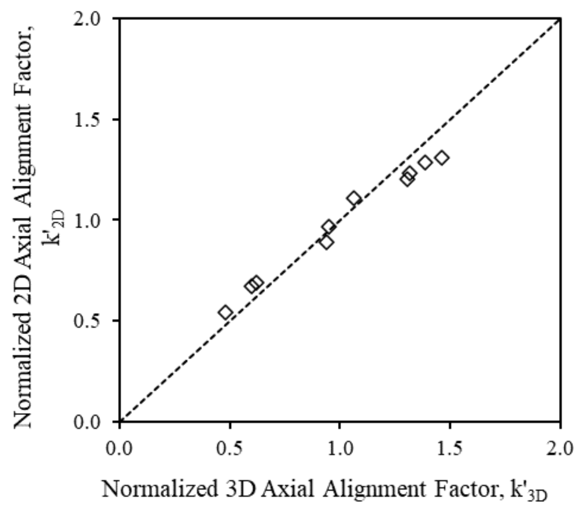


Figure 2. Comparison of fiber content (left) and normalized axial alignment factors (right) based on two- and three-dimensional analysis methods. Dashed line represents a line of equality.

To illustrate the spatial variation of fiber content and axial alignment factor within an individual specimen, digital "slices" of the 3D computed tomography scans were "cut" at 0.2-in. (5-mm) intervals over 2.6 inches along the longitudinal (vertical) axis of Core 52B and analyzed using the same 2D image analysis algorithm used for the physical samples. The spatial distribution of fiber volume and normalized axial alignment factor are illustrated in Figure 3. The 2D analysis indicates good agreement with the 3D fiber content on average. However, for this sample with k'_{3D} of 1.39 (substantially greater than 1.0, indicating a preferential alignment perpendicular to the cut plane), the normalized 2D axial alignment factor is consistently less than the 3D axial alignment factor obtained over the entire sample volume, though still greater than 1, indicating greater alignment perpendicular to the cut plane.

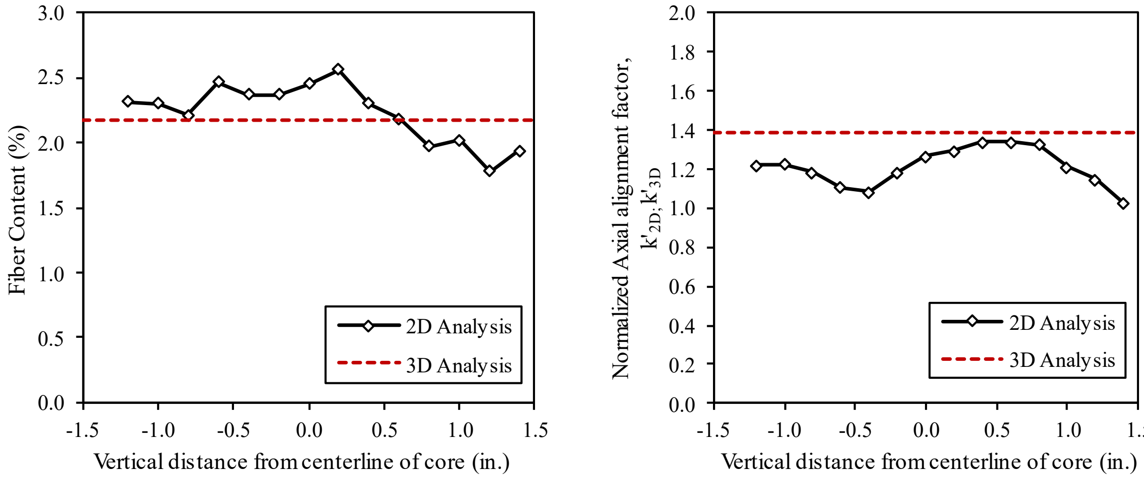


Figure 3. Spatial variation of fiber content (left) and axial alignment factor (right) along the longitudinal axis of Core 52B.

5. Discussion

3D imaging of fibers in UHPC using x-ray computed tomography is a powerful technique that can provide a complete understanding of fiber distribution and fiber orientation in the volume analyzed. Spatial trends in both fiber content and fiber alignment can be readily observed using this technique, and little to no sample preparation is required. However, the technique is constrained in its applicability due to limitations on sample size and the availability of specialized equipment and equipment operators. A 2D image analysis of cut sections can provide a reasonable alternative to 3D imaging for such purposes, as the technique is relatively easy to implement, quick to perform, and can provide satisfactory understanding of fiber quantity and distribution in many cases relevant to structural UHPC performance. The ability of 2D image analysis to accurately estimate the total fiber content and fiber alignment for a UHPC sample will depend on the selection of the surface(s) to be imaged, the quality of the sample preparation, and the process used for image thresholding (largely only relevant for fiber content).

Selection of surface(s) to be imaged has a potentially significant influence on the accuracy of the 2D analysis, particularly for samples that exhibit spatial variation in fiber quantity or orientation in planes not sectioned by the imaged "slice". Ideally, samples selected for 2D image analysis used for QA/QC will be sampled in areas for which fiber distribution and/or alignment are of concern, such as sections of a mock-up placement of an element where that element would be subject to tensile loads or areas for which non-uniform fiber distribution is suspected. Cut surfaces in these cases would be respectively oriented perpendicular to the direction of primary tensile loading, and parallel to the plane in which the non-uniform fiber distribution is anticipated.

In addition, the total surface imaged must appropriately represent the features of interest over the entire volume of interest: too small of an area (e.g., too small of a surface area or too few cut planes imaged) may result in poor estimates of fiber quantity and alignment for non-uniformly distributed fiber systems. In this study, it was generally observed that while variation in fiber content and/or alignment factor may have been observed for individual slices imaged for each sample, the fiber content and axial alignment factors exhibited reasonably close agreement with the results of the 3D analysis (Figure 2 and Figure 3). The noted exception was the slight under-estimation of axial alignment factors in 2D versus 3D observed at high alignment factors (i.e., fibers oriented more perpendicular to the cut plane).

The apparent bias in the axial alignment factor for the 2D image analysis appears to be related to challenges with 2D images accurately representing fibers with extreme orientations close to 0 degrees. Figure 4 shows histograms of fiber deviation angles for 2D and 3D analyses of Core I1. The 3D analysis indicated that this core exhibited very close to a random alignment of fibers relative to the reference axis ("x") for most deviation angles; however, fibers oriented near 0 degrees were under-represented in the 2D analyses for these cores as compared to the 3D analysis. The resolution of circular or near-circular features at low deviation angles by square pixels may result in a higher estimated deviation angle for these fibers due to an increased tendency to approximate circles as ellipses. Overall, the impact of under-representing fibers with preferential alignment (low deviation angles) is likely a conservative estimate of the fiber contribution to the tensile performance of a structural UHPC member.

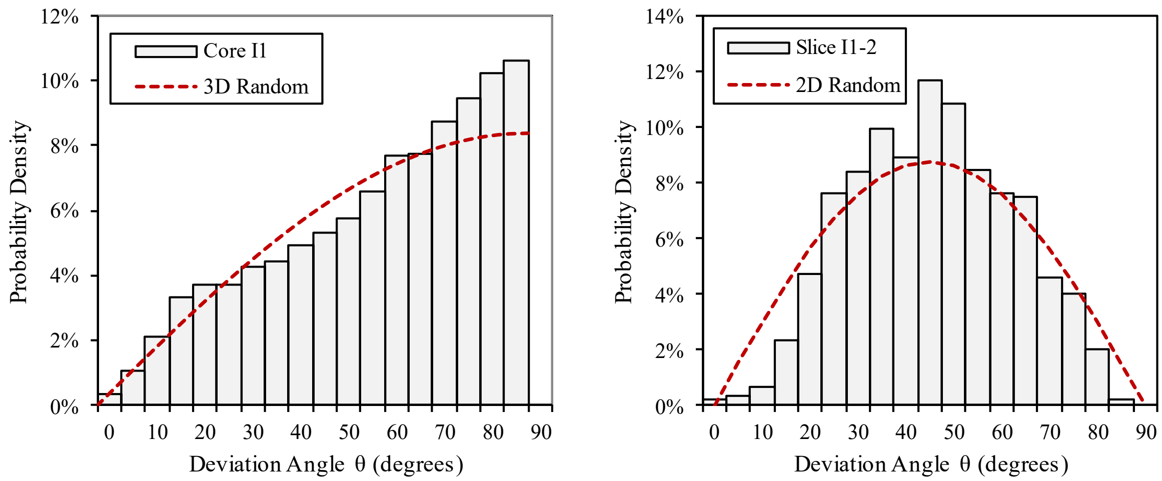


Figure 4. Histograms of fiber deviation angles for Core I1 in 3D (left) and 2D (right) analyses.

6. Conclusions and Recommendations

With proper sample selection, surface preparation, and color thresholding, 2D image analysis can provide suitable characterization of fiber content and fiber alignment for UHPC specimens for routine QA/QC purposes. While the fiber content obtained by 2D image analysis is sensitive to selection of color thresholds, the axial alignment factor is less sensitive to this operator-selected parameter of the analysis. The robustness of the axial alignment factor in 2D image analysis makes this technique well-suited for understanding the impact of fiber alignment on UHPC performance. 2D image analysis can be performed on sections cut from mock-up placements to better understand the impact of placement methods and element geometry on fiber orientation, or on laboratory test specimens following testing under direct tension or flexural test procedures to better understand the impact of sample fabrication procedures on the observed mechanical performance. The normalized axial alignment factors obtained can then be used in future designs to account for preferential alignment of fibers in as-placed members or to guide interpretation of laboratory test results as it relates to structural performance.

While 2D image analysis is well-suited for routine QA/QC and high-level characterization of fiber quantity and orientation, image analysis is limited in that it can only be applied to discrete cut surfaces, while 3D analysis can provide a more complete understanding of fiber distribution and alignment within an element. For applications requiring precise knowledge of fiber distribution or alignment, 3D analysis using advanced methods such as computed tomography may be preferable if the equipment is available and adequate volume can be analyzed.

Both 3D and 2D analysis methods are capable of characterizing fiber content and fiber alignment. However, because of geometric effects that differ between the two methods, method-specific normalizations, such those outlined herein, must be performed if the alignment factors calculated by each method are going to be compared or used as part of a standardized application, such as to establish a fiber alignment parameter for design.

7. Acknowledgements

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8. References

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