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Performance Assessment of Discontinuous Fibers in Fiber-Reinforced Concrete: Current State-of-the-Art

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Performance Assessment of Discontinuous Fibers in Ultra-High Performance Fiber-Reinforced Concrete: Current State-of-the-Art

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Abstract

Fiber-reinforced concretes have been developed and tested for years. During this development, the assessment of small discontinuous fibers has been critical in understanding the performance of these materials. Over the years, the understanding of fiber performance has been based on a single fiber pullout test. Through the years these tests have provided critical insight into individual fiber performance. This report provides insight into historical fiber performance assessments as well as introduces and explains new, novel techniques for understanding the effects of small discontinuous fibers and their performance characteristics.

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Preface

This study was conducted for Headquarters, U.S. Army Corps of Engineers for the Interfaces, Fiber Reinforcement, and Damage Mechanics Work Unit within the Materials and Modeling for Force Protection 6. 2 Work Package, Project number 458269.

The work was performed by the Structural Engineering Branch (StEB) of the Geosciences and Structures Division (GSD), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). At the time of publication, Mr. Charles W. Ertle II was Chief, StEB; Mr. James L. Davis was Chief, GSD; and Ms. Pamela G. Kinnebrew was Technical Director for Military Engineering. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Mr. Bartley P. Durst.

COL Bryan S. Green was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
foot-pounds force	1.355818	joules
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per square yard	0.542492	kilograms per square meter
kilopounds (force) (kip)	4448.222	newtons
kilopounds(force) per square inch (ksi)	6894.757	kilopascals
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters

1 Introduction

This report summarizes the research and development published in open literature regarding the assessment of fiber performance in both conventional fiber-reinforced concrete (FRC) and ultra-high performance fiber-reinforced concrete (UHPFRC). A brief background of FRC and UHPFRC is discussed in the remainder of Chapter 1. Chapter 2 will discuss traditional fiber performance assessment techniques and the current understandings of the data acquired through these techniques. Chapter 3 will investigate novel and more recent research approaches. Finally, a summary of the current state-of-the-art and future research recommendations will be discussed in Chapter 4.

1.1 Fiber-reinforced concrete

With the advancement in cementitious materials, the utilization of small discontinuous fibers to increase the ductility and toughness of these materials has increased (Astarluiglu et al. 2013; Willie and Naaman 2013; Naaman et al. 1991a; Lin and Li 1999; Maalej et al. 1995). Some of the earliest usage of fibers in concrete date back to the early 1900s by the usage of nails and wire segments. This advanced further into the 1960s with the use of steel fibers (ACI 2009; Romualdi and Batson 1963). Since then, the usage of glass, synthetic, and natural fibers have been studied (American Concrete Institute (ACI) 2009). With each of these fiber types, an increase in ductility, toughness, and serviceability was the goal. Unlike conventional reinforcement, fibers are added to the wet matrix and somewhat randomly distributed throughout the material. As the matrix material begins to yield, or crack, these small fibers begin to bridge these cracks transferring stress and limiting or reducing crack propagation (ACI 2009). This reduction in crack propagation induces numerous micro cracks, which promote and increase in ductility versus a single large macro crack typically seen in concrete yielding and failing. The early years of fiber-reinforced concrete consisted of cementitious matrices of conventional compressive strengths (3,000 – 5,000 psi). As the science of both fiber performance and matrix formulation advanced, ultra-high performance fiber-reinforced concretes (UHPFRCs) were developed.

1.2 Ultra-high performance fiber-reinforced concrete

Advanced cementitious materials have made major advancements over the last 40 years (Astarluiglu et al. 2013). Some of these materials are commercially available and reach compressive strengths similar to steel. However, as with most cementitious materials, the increase in compressive strength does not translate to the tensile regime. In order to obtain greater tensile capacity and ductility, these advanced materials incorporate small discontinuous fibers that are typically made of steel (Astarluiglu et al. 2013). These advanced, fiber-reinforced cementitious materials are classified based on their unconfined compressive strength. Ultra-high performance concretes (UHPCs) are advanced cementitious materials that have compressive strengths starting around 138 MPa (Astarluiglu et al. 2013).

Of particular interest, Cor-Tuf is a name given to a series of UHPCs developed by the Geotechnical and Structures Laboratory (GSL) at the U.S. Army Engineer Research and Development Center (ERDC) in Vicksburg, MS (Williams et al. 2009). Cor-Tuf has a typical unconfined compressive strength between 190 to 240 MPa and is broadly characterized as a reactive powder concrete (RPC). RPCs have fine aggregates and powders but do not include coarse aggregates. The maximum particle size found in Cor-Tuf is approximately 0.6 mm (Williams et al. 2009; Roth et al. 2010).

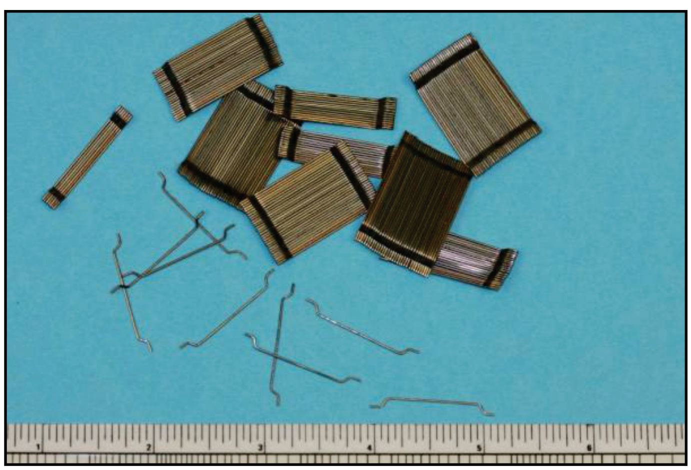
Mixture proportions for Cor-Tuf, as with most UHPCs, are carefully controlled to achieve desired properties, and slight changes can have a significant impact on the material's properties. The standard mixture proportions for Cor-Tuf are listed in Table 1. The mixture consists of fine silica sand, finely ground quartz flower, Portland cement, and micro-silica. A superplasticizer is included to aid in the reduction of water demands and increase workability (Williams et al. 2009; Roth et al. 2010). It should be noted that the original superplasticizer, WR Grace ADVA 170, is discontinued, and ADVA 190 is now used as the replacement. This superplasticizer allows for a water-to-cement ratio of about 0.21, which is considerably lower than the 0.40 typically seen in conventional concretes (Roth et al. 2010).

Table 1. Cor-Tuf mixture proportions (Williams et al. 2009; Roth et al. 2010).

Material	Product	Proportion by weight
Cement	Lafarge, Class H, Joppa, MO	1.00
Sand	US Silica, F55, Ottawa, IL	0.967
Silica flour	US Silica, Sil-co-Sil 75, Berkeley Springs, WV	0.277
Silica fume	Elkem, ES 900 W	0.389
Superplasticizer	W.R. Grace, ADVA 170/190	0.0171
Water (tap)	Vicksburg, MS municipal water	0.208
Steel fibers	N.V. Bekaert S.A., Dramix® ZP305	0.310

As seen in the Table 1, steel fibers are also typically added to the Cor-Tuf mixture to increase ductility. The fibers typically used are the Dramix® ZP305 from N.V. Bekaert S.A. as seen in Figure 1. These fibers are approximately 30 mm long with a diameter of 0.55 mm. Each end of the fibers has a slight deformation or hook and a tensile strength of approximately 1,100 MPa per the manufacturer (Williams et al. 2009; Roth et al. 2010). These fibers are attached together through a water-soluble adhesive that reacts with the water present during mixing to disperse throughout the mix.

Figure 1. Bekaert Dramix ® ZP305 steel fibers (Williams et al. 2009; Roth et al. 2010).



Cor-Tuf has been characterized both with and without fibers. The presence of fibers has shown to have little effect on most properties; however, it has the greatest effect on flexural and tensile properties (Roth et al. 2010). Table 2 shows the properties of Cor-Tuf both with and without fibers. For the initial elastic bulk modulus, K, Cor-Tuf with fibers is 25.2 GPa and 22.7 GPa without. The mean unconfined compressive strength was 237 and

210 MPa for with and without fibers, respectively. The tensile properties were originally characterized using direct pull tests. These showed an average tensile strength of -5.58 MPa and -8.88 MPa with and without fibers, respectively (Williams et al. 2009). Roth et al. (2010) investigated the tensile properties further by conducting split tensile tests. These tests showed a mean tensile strength for fiber-reinforced Cor-Tuf as 25.0 MPa and unreinforced as 10.4 MPa. This indicates a 240 percent increase with fiber reinforcement. For flexural response, 25-mm-thick beams were cast and tested using the four-point bending method (Roth et al. 2010). The flexural response showed a 162 percent increase between the mean values of fiber-reinforced and unreinforced specimen. The average flexural strength for fiber-reinforced was 25 MPa and unreinforced was 16 MPa (Roth et al. 2010). Finally, initial constrained and shear moduli were determined by using the results of the hydrostatic compression tests and calculated initial bulk modulus. The initial constrained modulus, M, for fiber-reinforced was 47.4 GPa, and unreinforced was 43.1 GPa. The initial shear modulus was 16.7 GPa and 15.3 GPa for reinforced and unreinforced, respectively (Williams et al. 2009).

Table 2. Cor-Tuf mechanical properties with and without fibers (Williams et al. 2009; Roth et al. 2010).

Property	Reinforced	Unreinforced
Initial bulk modulus (K)	25.2 GPa	22.7 GPa
Unconfined compression strength	237 MPa	210 MPa
Initial constrained modulus (M)	47.4 GPa	43.1 GPa
Initial shear modulus	16.7 GPa	15.3 GPa
Poisson's ratio	0.23	0.22
Specific gravity	2.93	2.77
Young's modulus		
Uniaxial strain test	40.9 GPa	37.5 GPa
Four point bending test (Avg.)	33.7 GPa	36.4 GPa
Tensile/flexural strength		
Direct pull test	5.58 MPa	8.88 MPa
Four point bending test (Avg.)	25.0 MPa	16.0 MPa
Splitting tensile test	25.0 MPa	10.4 MPa

There are several disadvantages to using UHPCs for structural applications. First and foremost are the constitutive materials. These materials have strict requirements with respect to quality and gradations (Williams et al. 2009;

Astarluiglu et al. 2013). Additionally, the mixing and placement process is also incredibly tedious and demanding. Some of these materials, including Cor-Tuf, require high-shear mixers and a rigorous curing regime typically including significant time in steam curing (Williams et al. 2009; Astarluiglu et al. 2013). The final issue to consider with UHPCs is unit cost compared to conventional strength or even high-strength concretes. One of the major expenses with UHPCs is the steel fibers, which are estimated at $400 per cu yd (Astarluiglu et al. 2013). With the significant cost of adding steel fibers, sufficient research has not been conducted to optimize their efficiency. Roth et al. (2010) noted that, when investigating the failure plane of the flexural specimens, most of the exposed fibers still had hooked ends. This shows that rather than the fiber being pulled from the matrix, the matrix fractured around the fiber. Some of the fibers were straightened showing the presumed failure method (Roth et al. 2010). This exposes the tendency for the matrix to fail around the fibers and confirms the need to investigate fiber reinforcement effects on the mesoscale. Additionally, fiber density, orientation, and fiber-to-fiber interactions need to be explored (Astarluiglu et al. 2013; Maalej et al. 1995).

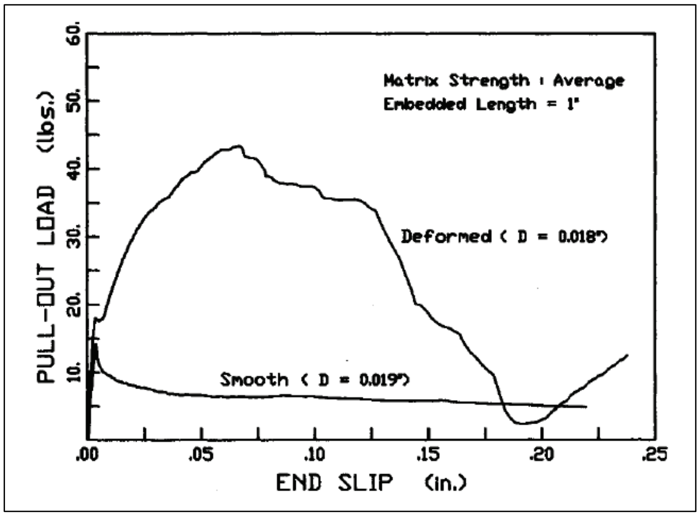
2 Traditional Approach

2.1 Single fiber pullout

The traditional approach for investigating fiber performance within UHPFRC concrete is through single fiber pullout tests. These tests are ideal for investigating fiber performance but more especially the fiber-matrix interfacial bond (Wille and Naaman 2013; Lin et al. 1999; Wang et al. 1988; Gray and Johnston 1984; Banthia and Trottier 1994; Astarluiglu et al. 2013). This experimental event is characterized by partially embedding a fiber within a matrix material and pulling the fiber from the matrix while capturing load and displacement. This load-displacement curve can also be considered as a bond versus slip curve when accounting for the embedded surface area. The fiber-matrix bond is essential to understanding the mechanical performance of fiber-reinforced composites (Naaman and Najm 1991; Lin et al. 1999; Katz and Li 1996). This allows for the capture of the two key parameters present within the fiber-matrix bond. These parameters are the chemical bond present between the fiber and matrix as well as the mechanical bond from fiber deformations or imperfections (Willie and Naaman 2012; Feng et al. 2014; Lin et al. 1999; Gray and Johnston 1984). For straight fibers, the primary failure mechanism is seen in the chemical bond between the fiber and matrix. For deformed fibers, the mechanical bond adds an increased resistance by inducing pressure on the matrix causing increased friction and larger pullout resistance (Wille and Naaman 2012).

The load versus slip curve can be defined by a sharp linear curve up to the maximum shear stress followed by a gradual decay until the fiber has been fully extracted from the matrix. This curve for both smooth and deformed fibers can be seen in Figure 2. The linear portion of this curve tends to have a steep slope, which implies that the chemical bond is brittle (Naaman et al. 1991a; Naaman et al. 1991b; Lin et al. 1999). The gradual decay is representative of the mechanical, or frictional, bond from fiber deformations and/or confinement from the surrounding matrix (Lin et al. 1999). This curve demonstrates that the fibers' energy absorption capabilities are highly dependent on the mechanical bond.

Figure 2. Typical fiber pullout curves for deformed and smooth fibers (Naaman and Najm 1991).



With the exception of Cusatis et al. (2015), the majority of the literature uses the single fiber pullout data to develop a mathematical model to replicate the pullout load versus slip curve. Early studies of fiber pullout focused on the correlation between bond strength and matrix compressive strength (Gray and Johnston 1984). Several of the initial mathematical models assumed a uniform shear stress bond with uniform bond strength across the embedded surface area of straight fibers (Wang et al. 1988; Naaman and Najm 1991). The models were improved by accounting for the non-uniform bond, or slip hardening (Wang et al. 1988; Lin et al. 1999). The later mechanics-based models accounted for criteria such as fiber rupture, alignment, and slip-dependent interfacial properties (Lin et al. 1999; Maalej et al. 1995). Banthia and Trottier (1994) studied the effects of deformed fibers and fiber inclination angles on the bond-slip characteristics.

With considerable efforts taken to characterize single fiber performance through pullout tests, there has been limited investigation done with respect to multiple fiber interaction and understanding fiber influence zones. There are mentions made in some papers that suggest that the matrix is not significantly affected by fiber debonding and pullout stating the assumption that the fiber creates a tunnel when pulled out with little matrix damage (Feng et al. 2014). However, others show quantifiable evidence that, with a higher-strength matrix material, premature failure of pullout tests occur due to brittle matrix splitting (Banthia and Trottier 1994). It is also noted in several publications that the effect of multiple fiber interaction is not taken into account and the overall effect of this interaction is unknown (Banthia and Trottier 1994; Naaman and Najm 1991; Lin et al. 1999).

Although significant effort has been put forth to accurately characterize single fiber interactions within a cementitious matrix as referenced above, this does not account for the composite action seen in advanced cementitious materials such as ultra-high performance concretes (UHPCs), since the probability of multiple fibers interacting together with the matrix is high. A more extensive, in-depth investigation into fiber influence zones and multiple fiber interactions is needed. By controlling several variables, such as fiber spacing, embedment length, and fiber geometry, a better understanding of these interactions can be quantified. These results can then be implemented into numerical codes, which can explicitly capture the fiber-matrix interactions and allow for further exploration into different fiber geometries as well as adjusting fiber-volume fractions to increase material performance.

2.2 Summary

FRCs are complex, heterogeneous cementitious materials. These materials, in general, can be characterized by having little to no large aggregates, low water-to-cement ratio, extensive admixtures to improve workability, and traditionally, small discontinuous fibers. These fibers can be made of several materials; however, for most commercially available UHPFRCs, steel fibers are used. The selection of fibers and their fiber-volume fraction are typically based on cost and wet mixture workability. When investigating the material properties at the macro-scale, it has been extensively reported that the matrix fractures around the fibers and little to no plastic deformation of the fibers are present.

When investigating fiber performance, the single fiber pullout test has been extensively explored and established as the norm. Through the extensive work of primarily Naaman and Li separately over the course of the last 30 years, a thorough understanding of the mechanics of a single fiber pullout has been investigated. However, with both researchers, their primary focus was on the fiber and plastic deformation of the fiber, very little consideration of the surrounding matrix, and no consideration of adjacent fibers.

3 Novel Approaches

As previously mentioned, the advancement of cementitious materials introduces complexities to the traditionally simplistic approaches to material characterization and development. With these advancements in materials, the approach to solving these problems has also advanced introducing new, novel techniques to solve traditional problems such as fiber performance. These techniques take into account advancements in computational power as well as the ability to treat advanced concretes more like the heterogeneous material that they are rather than the homogenous assumption of years past.

3.1 X-ray microtomography

One of the newer additions to material characterization experiments has been the utilization of X-ray microtomography (XMT). XMT utilizes a three-dimensional (3-D) map of the X-ray absorption of a material, which provides one of the most accurate methods for investigating the internal microstructure of concrete without additional damage to the specimen. The images are generated from a series of two-dimensional (2-D) radiographs that are reconstructed into a 3-D image (Trainor et al. 2013; Oesch 2015). From this 3-D image, a voxel intensity histogram can be generated in order to distinguish between different materials based on the X-ray attenuation. For example, the fibers will be a much brighter color than the cementitious matrix or air voids. This facilitates the ability to understand fiber distribution orientation as well as map crack propagations and quantify internal voids (Trainor et al. 2013; Oesch 2015). Figure 3 shows a digital image reconstruction of void mapping typically seen in XMT studies.

The ability to accurately distinguish these properties prompted studies by Trainor et al. (2013), Flanders et al. (2016), Oesch (2015), and Groeneveld (2016). Each of these studies investigated different aspects of the fiber performance effect on the composite material. Trainor et al. (2013) and Flanders et al. (2016) specifically investigated energy dissipation mechanisms in the fracturing of FRC during static and dynamic testing, respectively. With the work of load being described as the total energy dissipated during beam bending experiments, the majority of the energy dissipated was accounted for through matrix cracking, fiber pullout, fiber bending, and fiber bridging. For the static tests, 90 percent of the network of load was captured through these mechanisms (Trainor et al. 2013). The remaining 10 percent was estimated to be in the matrix cracking that was not visible through the XMT scans.

Figure 3. XMT image reconstruction showing voids within a damaged specimen (Oesch 2015).

Oesch (2015) and Groeneveld (2016) investigated how preferential fiber alignment affected static and dynamic tests, respectively. Oesch explored methods for mapping and quantifying damage as well as stiffness changes through the loading scheme. He also updated and advanced several Matlab scripts used during the image analysis (Oesch 2015). Groeneveld utilized Oesch's findings and scripts to investigate how preferential fiber directions affected the strain rate performance of the material. He conducted split-Hopkinson bar tests on cored samples from a long beam that used a placement technique to influence the fiber direction (Groeneveld 2016).

With the utilization of XMT, the effects of fiber performance can be studied by nondestructive means. However, these assessments to date have only focused on macro-scale investigations of the heterogeneous mixture and not on specific fiber characteristic performance.

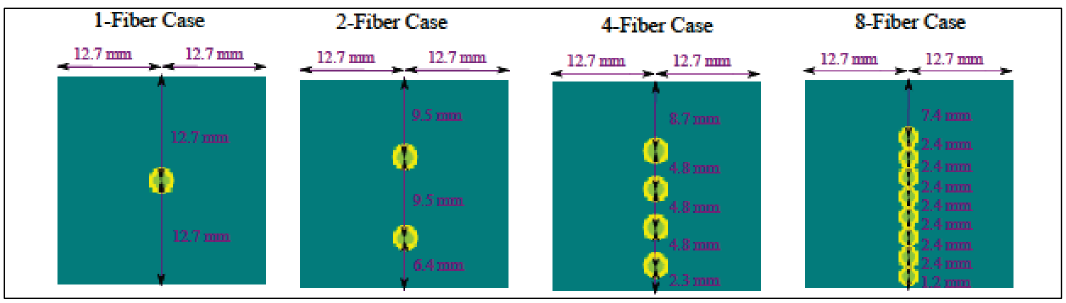
3.2 Multiple fiber interactions

With considerable efforts taken to characterize single fiber performance through pullout tests, there has been limited investigation conducted with respect to multiple fiber interaction and understanding fiber influence zones. There are mentions made in some publications that suggest that the matrix is not significantly affected by fiber debonding and pullout stating the assumption that the fiber creates a tunnel when pulled out with little matrix damage (Feng et al. 2014). However, others show quantifiable evidence that, with a higher-strength matrix material, premature failure of pullout tests occur due to brittle matrix splitting (Banthia and Trottier

1994). It is also noted in several publications that the effect of multiple fiber interaction has not been taken into account, and the overall effect of this interaction is unknown (Banthia and Trottier 1994; Naaman and Najm 1991; Lin et al. 1999).

Multiple fiber pullout tests have been conducted; however, these tests have several limitations. Cusatis et al. (2015) discusses a series of multiple fiber pullout tests conducted at Northwestern University. These tests showed similar results for the peak load for single and double fiber pullout. Differences began to appear when moving from two to eight fibers (Cusatis et al. 2015). If the fibers acted independently of each other, the peak pullout load would linearly increase with the number of fibers. This is not present in the results, which exposes the likelihood of fiber interactions due to proximity to other fibers (Cusatis et al. 2015). A key to this study was that, with increasing fiber content, the fiber-to-fiber spacing decreased. Figure 4 shows the cross section of the pullout specimen with the fiber spacing shown.

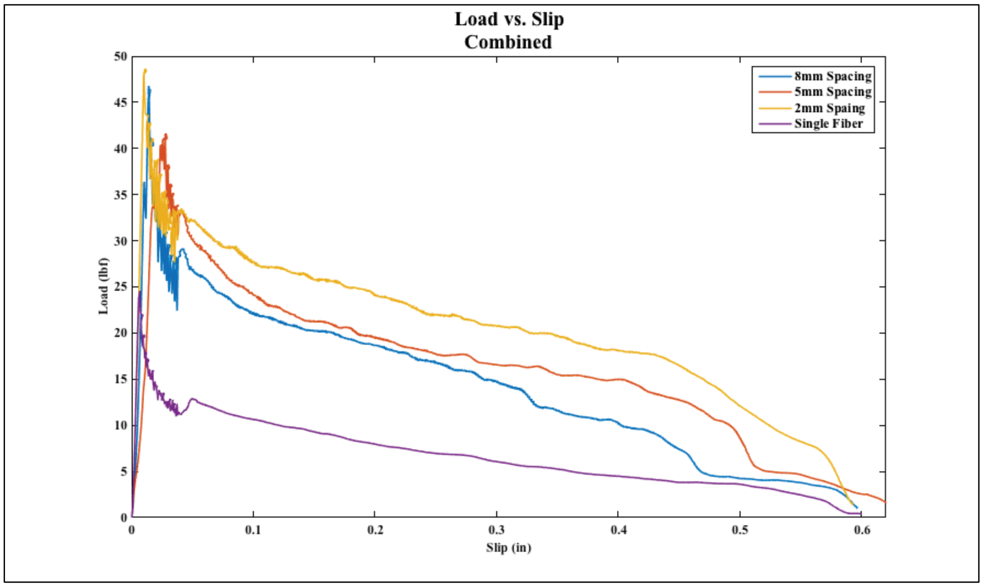
Figure 4. Specimen cross section for multiple fiber pullout tests (Cusatis et al. 2015).



Understanding the limitations of the previous multiple fiber testing as well as the shortcomings of single fiber experiments, the author recently developed and is currently investigating a new technique for understanding fiber-to-fiber interactions and fiber influence zones. The on-going study utilizes newly developed pullout specimens to capture pullout-vs-slip data while controlling fiber size, spacing, embedment length, and geometry. Initial results of two-fiber tests show that an optimal fiber spacing window may be present.[1] Based on the above research conducted by Cusatis et al. (2015), fiber spacing was varied between 8 and 2 mm for the initial tests while comparing them to single fiber tests. Figure 5 shows the load-vs-slip curves for each spacing and the single fiber tests.

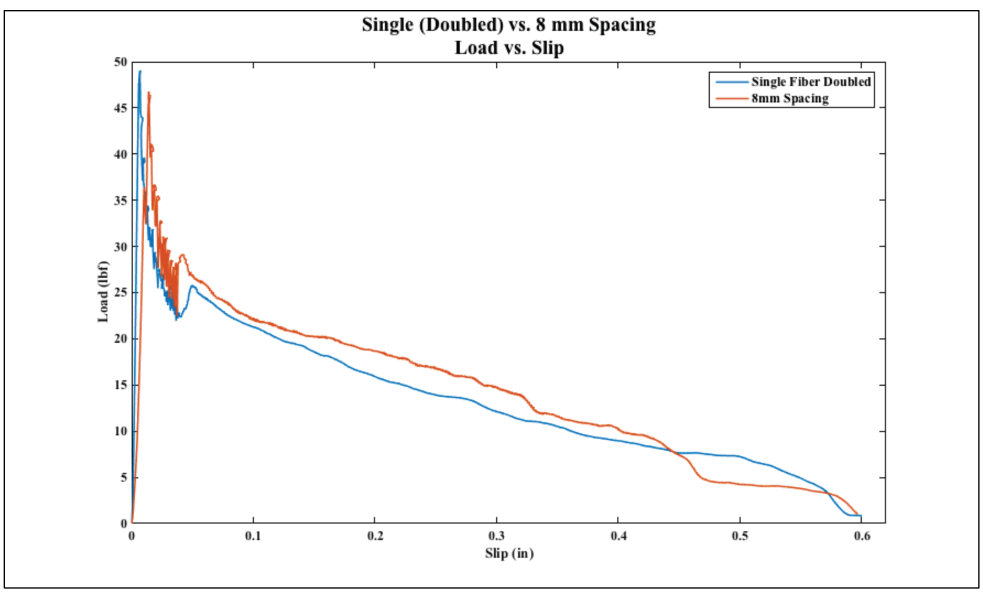
[1] Burchfield, C. A. 2016. Fiber influence zone effect on multiple fiber interactions within ultra high performance fiber-reinforced concrete. PhD Proposal. Gainesville, FL: The University of Florida.

Figure 5. Load vs. slip curves for initial fiber spacing tests (Burchfield 2016).



Based on the overall shape of the curves, it appeared that there were similarities with the 8-mm spacing and the single fiber tests. For comparative purposes, the single fiber test load data were doubled and plotted with that of the 8-mm spacing. Figure 6 shows the 8-mm spacing with the doubled single fiber data. This exposes the potential for an upper bound to the fiber spacing window.

Figure 6. Comparison of 8-mm spacing to load doubled for a single fiber test (Burchfield 2016).



As previously mentioned, this particular study is ongoing. As this program begins to wrap up, additional publications will be available with a more complete understanding of the fiber spacing window and fiber-to-fiber interactions.

3.3 Summary

With the advancement of technology, the capability to assess the performance characteristics of fiber-reinforced concrete has also advanced. With the additional novel techniques and multiple fiber pullout, the ability to assess the performance of fibers has also improved. However, there is still a lack of knowledge in understanding the true performance of multiple fibers interacting not only across cracks or voids but also how these fibers interact with each other. Initial investigations by Cusatis et al. (2015) and Burchfield (2016) show that the assessment of multiple fibers is necessary to truly understand the fiber performance on the macro scale. With the capabilities described utilizing XMT, these multiple fiber interactions can be further evaluated at a larger scale.

4 Conclusions

4.1 Overview

Fiber performance assessments have been extensively explored for many years. These assessments have essentially focused primarily on the performance of a single fiber within a cementitious matrix. With each additional step, a better understanding of the mechanics of fiber pullout has been determined, and in most cases, a micromechanical model has been improved to incorporate the new discoveries. However, this has some considerable limitations when considering the typical usages of fibers as well as the overall heterogeneity of fiber-reinforced concretes.

When considering alternative methods to better understand fiber performance, several techniques have been utilized. First, X-ray microtomography has been utilized to non-destructively evaluate fiber distributions, orientation, and FRC posttest damage. This technique allows for a closer to meso scale investigation of the effects of numerous fibers on the performance of the material. These investigations have been able to account for the majority of the performance characteristics in the materials, which provide a huge leap forward in the understanding and performance characteristics of these highly advanced materials. Additionally, a few individuals have conducted multiple fiber pullout experiments. These tests also provide critical insight into the interactions of fibers as well as a better understanding of the cumulative effects of fibers.

4.2 Path forward

As new materials are developed, developing and utilizing new, novel techniques for understanding multiple fiber interactions is critical to understanding the performance enhancements provided by fiber reinforcement. The ability to assess characteristics of multiple fibers is more characteristic of the heterogeneity of the materials and thus provides the critical insight needed. This will also promote the ability to optimize current materials as well as select fibers based on desired performance.

X-ray microtomography is a vital tool for nondestructive testing and evaluation of materials. This capability promotes the assessment of fiber distributions and orientations that can feed the experimental test matrix for multiple fiber tests. This will help to understand the current materials characteristics as well as allowing for fiber dosage modifications to improve statistical distributions in an effort to improve these materials. XMT will also promote a better understanding of how fibers are dispersed during the mixing process and how changing fiber types can change distribution patterns.

Multiple fiber pullout experiments provide insight into how fiber geometry changes affect the larger-scale performance of a material. By manipulating fiber configurations in a small scale test such as these, the effects of fiber diameter and geometry can be understood, which can lead to fiber dosage changes as well as an enhancement to desired performance based solely on fiber manipulation.

As seen, combining these techniques also shows considerable promise. Utilizing these two methods promotes an extensive understanding of fiber performance all the while optimizing the material and improving desired performance by designing materials based on individual constituent performance.

References

American Concrete Institute (ACI). 2009. *Report on fiber reinforced concrete*. Designation 544.1R-96. Farmington Hills, MI: American Concrete Institute.

Astarlioglu, S., T. Krauthammer, and C. Felice. 2013. *State-of-the-art report on fiber-reinforced, ultra-high performance concrete (2nd Edition)*. Center for Infrastructure Protection and Physical Security. Gainesville, FL: University of Florida.

Banthia, N., and J.-F. Trottier. 1994. Concrete reinforced with deformed steel fibers, Part I: Bond-slip mechanisms. *Materials Journal* 91 (5). doi:10.14359/4059.

Cusatis, G., C. Ji, M. Du, and J. Smith. 2015. Experimental and numerical characterization of pullout behavior of hooked steel fibers in ultra high performance cementitious matrix. rep. *Experimental and numerical characterization of pullout behavior of hooked steel fibers in ultra high performance cementitious matrix*. Evanston, IL: Northwestern University.

Feng, J., W.W. Sun, X.M. Wang, and X.Y. Shi. 2014. Mechanical analyses of hooked fiber pullout performance in ultra-high-performance concrete. *Construction and Building Materials* 69 (October): 403–10. doi:10.1016/j.conbuildmat.2014.07.049.

Flanders, L. S., T. Rushing and E. N. Landis. 2016. Energy dissipation mechanisms in the fracture of reinforced ultra high performance concrete. Proceedings of the 4th International Symposium on Ultra-High Performance Concrete and High Performance Construction Materials, HiPerMat 2016, E. Fehling, B. Middendorf, and J. Thiemicke, eds., 9-11 March, 2016, Kassel, Germany.

Gray, R.J., and C.D. Johnston. 1984. The effect of matrix composition on fibre/matrix interfacial bond shear strength in fibre-reinforced mortar. *Cement and Concrete Research* 14 (2): 285–96. doi:10.1016/0008-8846(84)90116-9.

Groeneveld, A.B. 2016. Effect of fiber orientation on dynamic compressive properties of an ultra-high performance concrete. Open access MS thesis, Michigan Technological University. http://digitalcommons.mtu.edu/etdr/163

Katz, A., and V. C. Li. 1996. A special technique for determining the bond strength of micro-fibres in cement matrix by pullout test. *Journal of Materials Science Letters* 15 (20): 1821–23.

Lin, Z., T. Kanda, and V. C. Li. 1999. On interface property characterization and performance of fiber-reinforced cementitious composites. *Concrete Science And Engineering* 1: 173–184.

Maalej, M., V. Li, and T. Hashida. 1995. Effect of fiber rupture on tensile properties of short fiber composites. *Journal of Engineering Mechanics* 121 (8): 903–13. doi:10.1061/(ASCE)0733-9399(1995)121:8(903).

Naaman, A. E., and H. Najm. 1991. Bond-slip mechanisms of steel fibers in concrete. *ACI Materials Journal* 88 (2). http://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&i=1896.

Naaman, A. E., G. G. Namur, J.M. Alwan, and H.S. Nam. 1991a. Fiber pullout and bond slip. I: Analytical study. *Journal Of Structural Engineering* 117 (9): 2769–2790.

Naaman, A.E., G.G. Namur, J.M. Alwan, and H.S. Nam. 1991b. Fiber pullout and bond slip. II: Experimental validation. *Journal of Structural Engineering* 117 (9): 2791–2800.

Oesch, T.S. 2015. *Investigation of fiber and cracking behavior for conventional and ultra-high performance concretes using x-ray computed tomography*. PhD diss. University of Illinois at Urbana-Champaign, Urbana, IL, USA.

Romualdi, J.P., and G.B. Batson. 1963. Mechanics of crack arrest in concrete. Proceedings, ASCE, 89: EM3, June 1963, 147-168.

Roth, M.J., T. S. Rushing, O.G. Flores, D.K. Sham, and J.W. Stevens. 2010. *Laboratory investigation of the characterization of cor-tuf flexural and splitting tensile properties*. ERDC/GSL TR-10-46. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Trainor, K.J., B.W. Foust, and E.N. Landis. 2013. Measurement of energy dissipation mechanisms in the fracture of fiber-reinforced ultrahigh-strength cement-based composites. *Journal of Engineering Mechanics* July 2013. 139 (7): 771-779.

Wang, Y., V.C. Li, and S. Backer. 1988. Modelling of fibre pull-out from a cement matrix. *International Journal of Cement Composites and Lightweight Concrete* 10 (3): 143–49. doi:10.1016/0262-5075(88)90002-4.

Wille, K., and A.E. Naaman. 2012. Pullout behavior of high-strength steel fibers embedded in ultra-high-performance concrete. *ACI Materials Journal* 109 (4). http://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&i=51683923.

Wille, K., and A.E. Naaman. 2013. Effect of ultra-high-performance concrete on pullout behavior of high-strength brass-coated straight steel fibers. *ACI Materials Journal* 110 (4). http://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&i=51685792.

Williams, E.M., S.S. Graham, P.A. Reed, and T.S. Rushing. 2009. *Laboratory characterization of cor-tuf concrete with and without steel fibers*. Technical Report TR-09-22. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

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Fiber reinforced concretes have been developed and tested for years. During this development, the assessment of small discontinuous fibers has been critical in understanding the performance of these materials. Over the years, the understanding of fiber performance has been based on a single fiber pullout test. Through the years these tests have provided critical insight into individual fiber performance. This report provides insight into historical fiber performance assessments as well as introduces and explains new, novel techniques for understanding the effects of small discontinuous fibers and their performance characteristics.

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