Tensile Properties of UHP-FRC Reinforced with High-Strength Steel Hooked Fibers and Ultra-High-Performance Slurry Infiltrated Fiber-Reinforced Concrete (UHP-SIFCON)

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Abstract

This paper presents experimental studies conducted on the tensile properties of ultra-high-performance fiber-reinforced concrete (UHP-FRC) reinforced with high-strength steel hooked fibers with a fiber volume fraction of 1.5%, 2%, 2.25%, and 2.4%. A comparison is made between its behavior and that of UHP-FRC reinforced with commonly used high-strength straight smooth steel fibers. The experimental results indicate that UHP-FRCs reinforced with steel hooked fibers exhibited greater tensile strength (except for the 1.5% fiber volume fraction) and ductility than UHP-FRCs reinforced with straight smooth steel fibers. Additionally, the use of hooked fibers enables the production of UHP-FRC by pre-placing the fibers in the mold, followed by slurry infiltration with UHPC materials. This method results in the production of ultra-high-performance slurry infiltrated fiber-reinforced concrete (UHP-SIFCON) that enables the incorporation of a high fiber dosage. This, in turn, leads to the highest possible mechanical properties, such as strength and ductility, in UHP-FRCs. Based on the experimental results, it was found that the UHP-SIFCON produced (with a steel hooked fiber volume fraction of 7.5%) exhibited exceptional toughness. Specifically, it maintained a high compressive strength of over 33 ksi (228 MPa) up to a compressive strain of approximately 9% and a tensile strength of around 2.4 ksi (17 MPa) until a tensile strain of about 1.2%. UHP-SIFCON exhibits a considerably better tensile performance compared to conventional UHP-FRCs with 3% straight smooth steel fibers, which generally maintain a peak tensile strength of 1.1 ksi (7.6 MPa) up to approximately 0.3% tensile strain.

Keywords: UHP-FRC, Direct Tensile Test, Strain-Hardening, Hooked Fiber, SIFCON.

1. Introduction

In order to fully utilize the benefits of UHP-FRC in structural applications, it is crucial to obtain strain-hardening behavior that not only exhibits high tensile strength after cracking, but also high tensile strains (Figure 1(b), Naaman, 2017). This is especially important for the effective application of UHP-FRCs in structural members, as it can result in enhanced strength, ductility, and energy absorption capacity under both static and cyclic loading conditions. Figure 1(c) suggests that a higher value of ε_{pc} (which represents the strain at the peak tensile stress, σ_{pc}) leads to a more substantial contribution of UHP-FRC to the nominal bending resistance of the section. Therefore, attaining a significant strain at the maximum stress is a vital factor for structural applications of UHP-FRC. A recent study involving a vast amount of test data on UHP-FRC (Naaman and Shah, 2022) has suggested that a design value of $\varepsilon_{pc} = 0.002$ is appropriate for UHP-FRC that contains 2% volume fraction of smooth steel fibers. Their review also suggests that UHP-FRC produced through premixing with a volume fraction of approximately 2 to 4% of smooth steel fibers can hardly attain a strain at peak stress greater than 0.005. It is important to note that a minimum reinforcement tensile strain of 0.005 is mandated by design codes (ACI, 2019; AASHTO, 2020) for a tension-controlled flexural structural member.

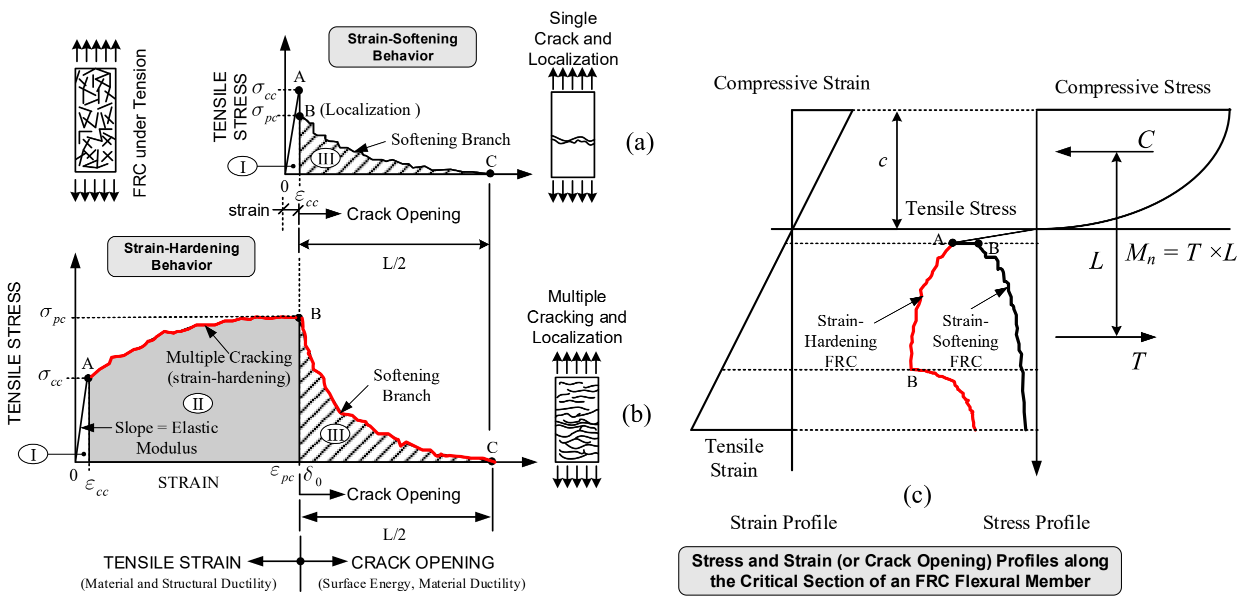

Figure 1: (a) typical tensile stress-strain (crack opening) curve for strain-softening FRCs, (b) typical tensile stress-strain (crack opening) curve for strain-hardening FRCs, (c) bending moment determined by utilizing the tensile stress profile

For steel-fiber reinforced FRCs/UHP-FRCs, Naaman (2017) and Naaman and Shah (2022) identified three main factors that lead to an enhancement in their strain capacity at peak stress, ε_{pc}. These include the volume fraction of fibers (V_f), the aspect ratio of fibers (length/diameter, l/d), and the use of mechanically deformed fibers (such as steel hooked fibers) and/or those that exhibit a slip-hardening bond characteristic. At present, high-strength straight smooth steel fibers with a volume fraction ranging from 1 to 3% are predominantly used in UHP-FRCs. Earlier studies have indicated that straight smooth steel fibers demonstrate slip-hardening behavior when they are being pulled out of UHPC (Wille and Naaman, 2013). This is because of the following three factors: (1) wedge effect of adhered and abraded particles along the fiber, (2) scratching of the fiber surface, thus scraping its brass coating, and (3) fiber end deformation due to the cutting process.

Despite the widespread use of steel hooked fibers in FRCs, there has been very limited research conducted on their application in UHP-FRCs. The hooked ends of these fibers offer a robust mechanical bond that has the potential to improve strain capacity at peak stress, ε_{pc}. According to Qiu et al. (2022), the addition of 2% steel hooked fibers (measuring 13 mm in length and 0.22 mm in diameter) to UHPC resulted in a more prominent tensile strain-hardening behavior than UHPC with straight smooth fibers, primarily due to the mechanical anchorage of the hooked fibers. Further investigation is required to determine if this finding is applicable to UHP-FRCs with different fiber volume fractions.

The process of manufacturing slurry infiltrated fiber-reinforced concrete (SIFCON) involves filling a mold to its maximum capacity with steel hooked fibers and then infiltrating the resulting fiber network with a fine-grain cement-based slurry (Naaman, 2017). The fiber content in SIFCON can usually range from 5% to 15%. Commonly used short, smooth, straight fibers in conventional UHP-FRCs are unsuitable for manufacturing SIFCON as they cannot create a fiber network due to the lack of interlocking caused by fiber deformation. By enabling the use of the maximum possible volume fraction of a specific fiber, SIFCON results in the highest attainable mechanical properties of FRCs. SIFCON, when using conventional concrete, has demonstrated exceptionally high strain capacities. The significant strain capacities are attributed to the high fiber content and the interlocking of fibers facilitated by the hooked ends, which are absent in FRCs with low fiber content (Naaman and Shah, 2022).

Given that steel hooked fibers with a high tensile strength (thus high plastic bending capacity at the hooked ends) exceeding 435 ksi (3,000 MPa) and UHPC matrices with compressive strength exceeding 138 ksi (20 MPa) are available on the market, it is anticipated that the use of ultra-high-performance slurry infiltrated fiber-reinforced concrete (UHP-SIFCON) has much enhanced strain and strength capabilities.

This study aimed to investigate the tensile strain capabilities of typical UHP-FRCs that were reinforced using high-strength steel hooked fibers with fiber volume fractions of 1.5%, 2%, 2.25%, and 2.4%. It is worth noting that when the fiber volume fraction exceeds 2.25%, the mixing process becomes difficult due to the presence of hooks on the fibers. Furthermore, it aimed to evaluate the tensile mechanical properties of UHP-SIFCON, which was reinforced with steel hooked fibers having a fiber volume fraction of 7.5%.

2. Conventional UHP-FRC subjected to Direct Tensile Test (DTT)

Figure 2 shows the two types of steel fibers used in this study, while Table 1 provides a summary of their properties. As discussed in the Introduction, the strain capacity at peak stress (ε_{pc}) of UHP-FRCs is influenced by various factors, such as the fiber volume fraction, aspect ratio of fibers, and bond characteristics. Table 1 presents the values of these parameters obtained from previous research, as well as the results obtained from the single-fiber pullout test conducted in this study (Figure 3). Figure 3 indicates a slip-hardening behavior when the hooked fiber was pulled out from UHPC. To determine the average bond strength at the interface between a hooked fiber and matrix, τ_{av}, the following Equation (1) was utilized (Wille and Naaman, 2013; Naaman, 2017):

$$\tau_{av} = \frac{P_{max}}{\pi d \left(L_e\right)} \tag{1}$$

where P_{max} is the average maximum pullout load and L_e represents the initial embedded length, which is equivalent to one-quarter of the fiber length.

Figure 2: High-strength steel hooked fiber and steel straight smooth fibers used in this study

Table 1. Steel fiber types and properties used in the experimental study

Fiber	Diameter* (d), mm	Length* (l), mm	Aspect Ratio (l/d)	Tensile Strength, MPa (ksi)	Average bond strength (τ_{av}), MPa (ksi)	Fiber Volume Fraction (V_f)	Reinforcing index ($\tau_{av}V_f l/d$)
Straight smooth fiber (Bekaert OL 13/.20)	0.175	12.5	71.4	2,160 (313)	14.4** (2.1)	1.5%	15
Hooked fiber (Bekaert 3D 80/30)	0.38	30	80	3,070 (455)	24.8*** (3.6)	1.5%	30
						7.5% (SIFCON)	150

**The average length and diameter of fibers were obtained from 5 random samples; **maximum value from Wille and Naaman (2013); ***this study (Eq. 1 and Figure 3); 1 mm = 0.04 in., 1MPa = 0.145 ksi*

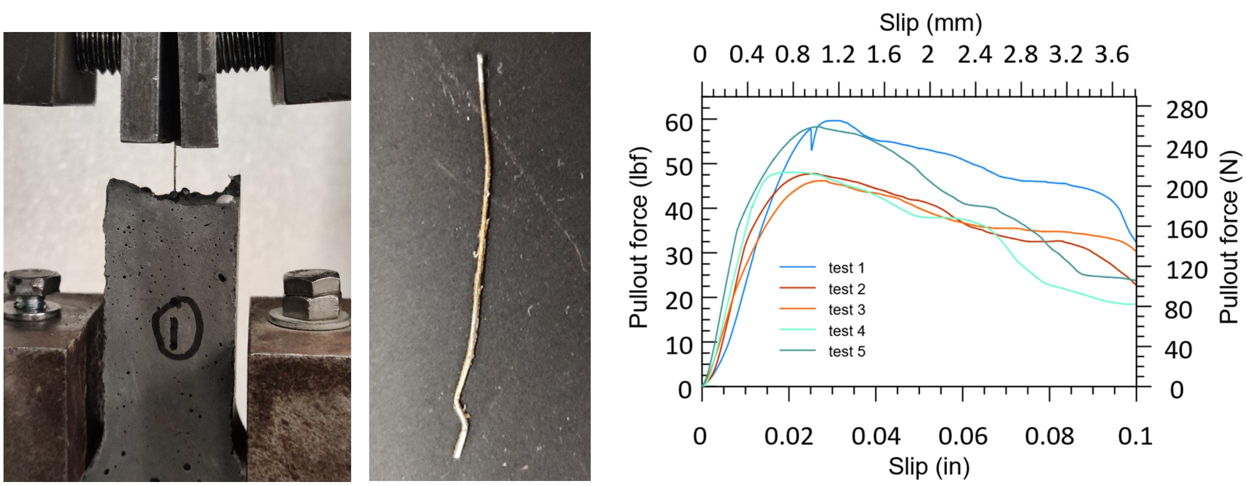

Figure 3: Single-fiber pullout test setup and results

Previous research has indicated that smaller-sized tensile specimens typically exhibit greater values of peak tensile stresses and strains (Aghdasi et al., 2016; Naaman and Shah, 2022). In this study, a large-sized direct tensile test (DTT) specimen was utilized, which had a cross-sectional area of 16 in.^{2} [10,323 mm^2], with a width and depth of 4 in. × 4 in. [101.6 mm × 101.6 mm], satisfying the requirement of having dimensions at least three times the fiber length (ASTM, 2019).

The mixture design for UHP-FRC was similar to the one reported in Aghdasi et al.'s study (2016), yielding a compressive strength of approximately 18 ksi (125 MPa). The tensile stress versus strain curves and cracking patterns obtained from DTT for UHP-FRC with steel straight smooth and hooked fiber volume fractions of 1.5%, 2%, 2.25%, and 2.4% are presented in Figure 4 and Figure 5, respectively.

Figure 4 illustrates that the strain capacities at peak stress (ε_{pc}) for UHP-FRCs with high-strength steel hooked fibers varied from roughly 0.3% to 0.6%, whereas those of UHP-FRCs containing high-strength steel straight smooth fibers ranged from 0.1% to 0.4%. If everything else being equal, the test results suggest that utilizing high-strength steel hooked fibers enables UHP-FRCs to achieve superior tensile strain capacity. Notably, UHP-FRCs containing 2.4% steel hooked fibers did not exhibit a greater ε_{pc} compared to those with 2% or 2.25% steel hooked fibers. This is attributed to challenges in the mixing process when the steel hooked fiber dosage exceeds 2.25%. Figure 4 also shows that UHP-FRCs containing high-strength steel hooked fibers exhibited greater peak tensile stresses than UHP-FRCs containing high-strength steel straight smooth fibers, except for when the fiber volume fraction was 1.5%. The enhanced tensile properties of UHP-FRCs containing steel hooked fibers can be explained by their higher reinforcing index ($\tau_{av} V_f l/d$), as shown in Table 1.

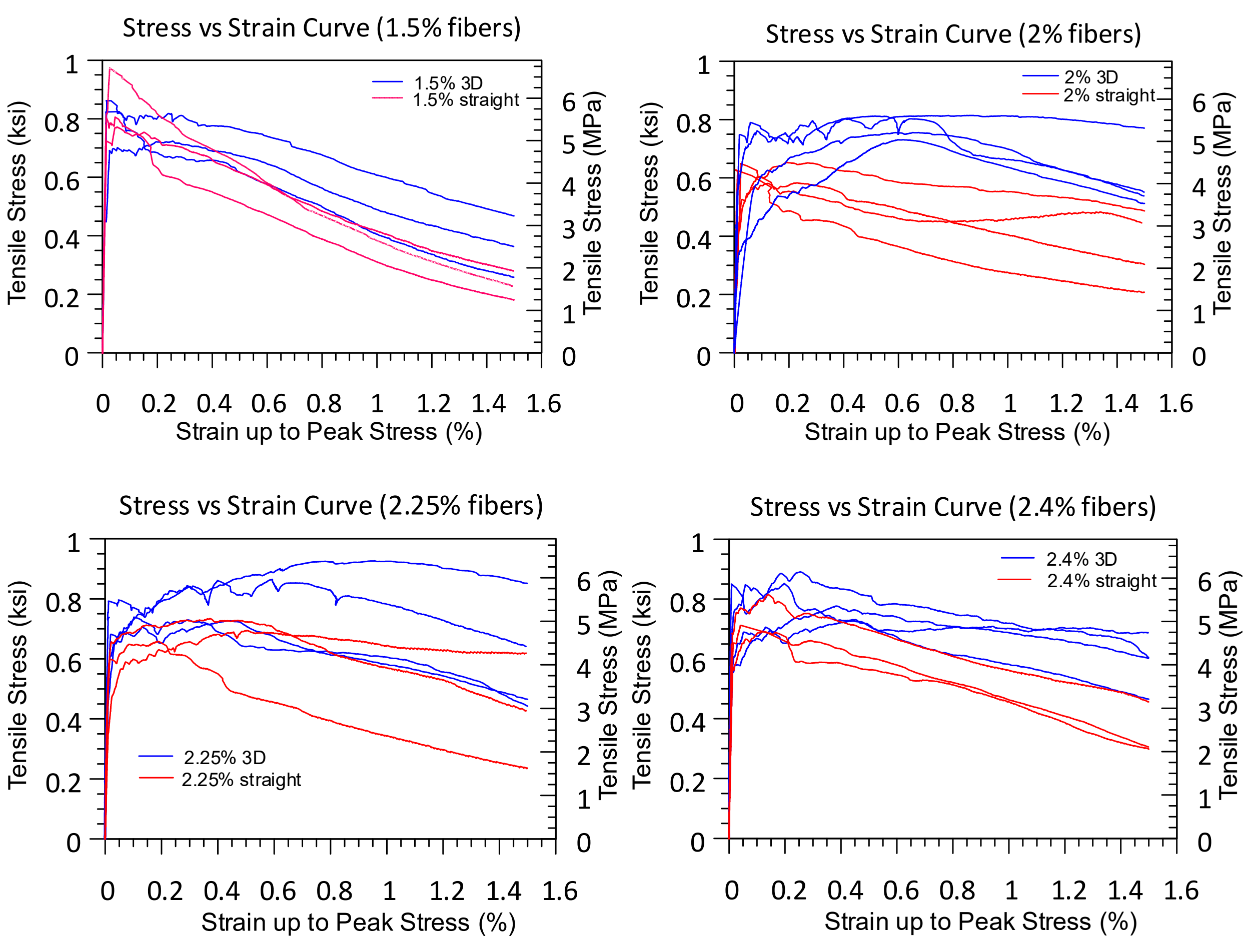

Figure 4: Direct tensile test results of UHP-FRCs with fiber volume fractions of 1.5%, 2%, 2.25%, and 2.4%

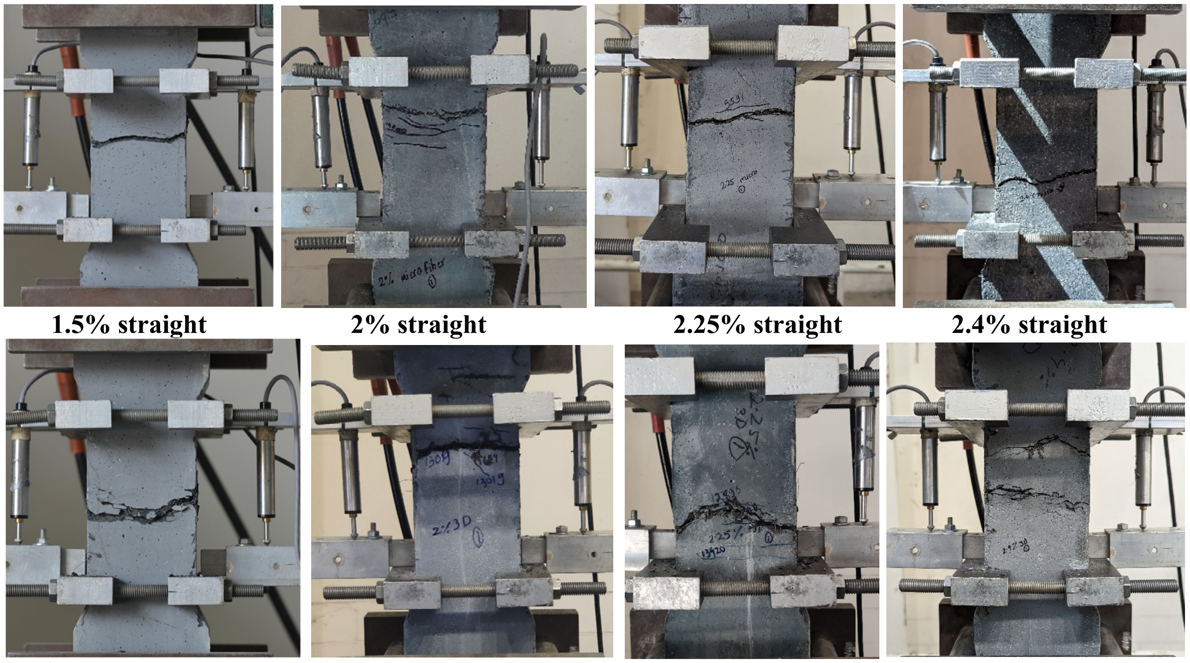

Figure 5: Cracking patterns of UHP-FRCs with fiber volume fractions of 1.5%, 2%, 2.25%, and 2.4%

3. UHP-SIFCON subjected to Direct Tensile Test (DTT)

Figure 6 shows the fabrication process of UHP-SIFCON tensile specimens with a steel hooked fiber volume fraction of 7.5%.

Figure 6: Fabrication of UHP-SIFCON tensile specimen with a fiber volume fraction of 7.5%

To compare the tensile performance of UHP-SIFCON and conventional UHP-FRC, UHP-FRC tensile specimens were prepared using high-strength steel straight smooth fibers. The maximum fiber dosage of smooth straight fibers (Figure 2 and Table 1) that can be incorporated into UHPCs using conventional mixing procedures is approximately 3% volume fraction. According to Figure 7, UHP-SIFCON exhibited remarkable toughness and sustained a high tensile stress of around 2.4 ksi (17 MPa) until a tensile strain ε_{pc} of roughly 1.2%. This can be attributed to the very high reinforcing index of UHP-SIFCON (Table 1) and the fiber-to-fiber interlock. In contrast, conventional UHP-FRCs containing 3% straight smooth steel fibers maintained a maximum tensile strength of about 1.1 ksi (7.6 MPa) up to a tensile strain ε_{pc} of approximately 0.3%. Figure 8 illustrates the multiple cracking in the tensile specimens, which reflects the higher strain capacity of UHP-SIFCON. Figure 9 shows the typical compressive stress-strain responses of UHP-SIFCON and conventional UHP-FRC. UHP-SIFCON was able to sustain a high compressive stress of 33 ksi (228 MPa) up to a compressive strain of around 9%, which is about 30 times the compressive strain capability of plain concrete. In contrast, conventional UHP-FRC exhibited significantly lower compressive strength, toughness, and strain capabilities.

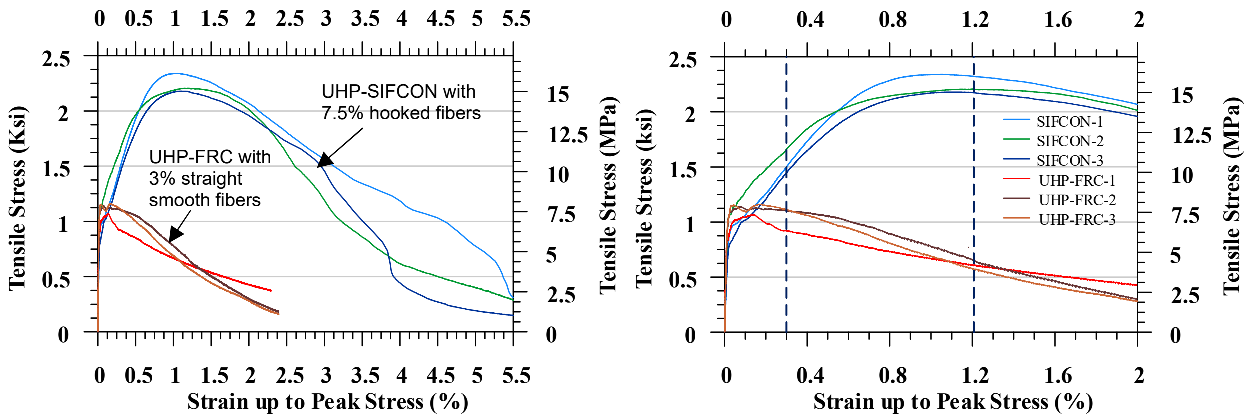

Figure 7: Direct tensile test results of UHP-FRCs with 3% straight smooth fibers and UHP-SIFCONs with 7.5% hooked fibers

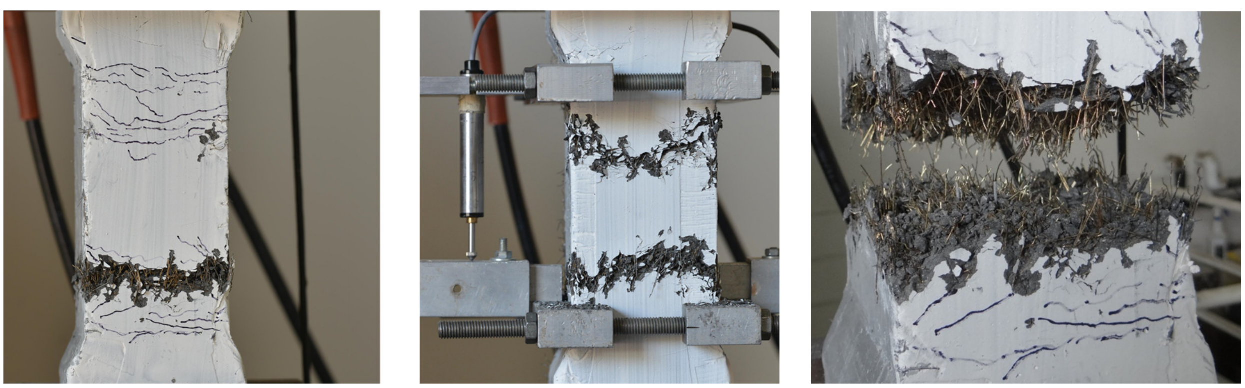

Figure 8: Typical UHP-SIFCON specimens with fiber volume fractions of 7.5%

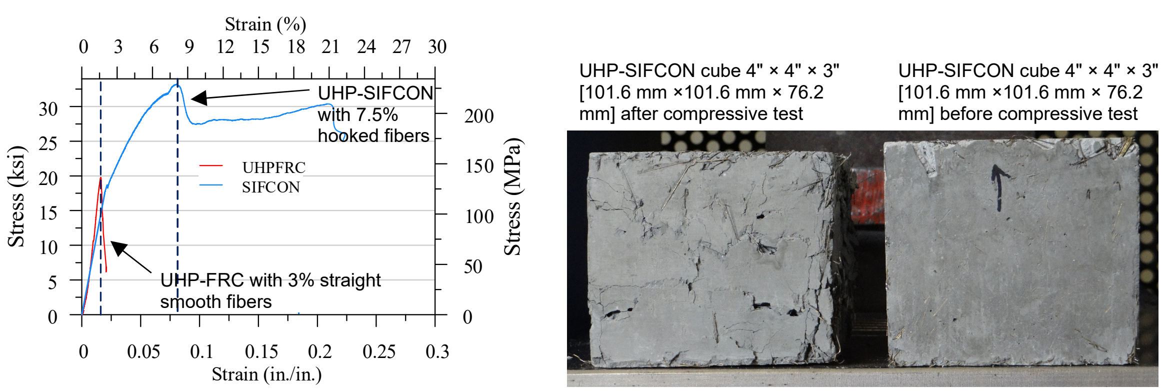

Figure 9: Typical UHP-SIFCON specimens with fiber volume fractions of 7.5%

4. Summary and Conclusions

Achieving a notable strain capacity in UHP-FRCs would offer significant benefits in structural applications. However, commonly used UHP-FRCs have a tensile strain capacity at peak stress, ε_{pc}, of less than 0.004 (Naaman and Shah, 2022). Naaman (2017) and Naaman and Shah (2022) have identified three primary factors that can enhance the tensile strain capacity of UHP-FRCs: (1) increasing the volume fraction of fibers (V_f), (2) increasing the aspect ratio of fibers (length/diameter, l/d), and (3) incorporating mechanically deformed fibers and/or fibers with a slip-hardening bond characteristic. This study utilized high-strength steel hooked fibers in place of the commonly used steel straight smooth fibers due to their greater mechanical bond strength and slip-hardening bond characteristics. Additionally, their aspect ratio is slightly higher, leading to a reinforcing index ($\tau_{av} V_f\, l/d$) that is twice that of steel straight smooth fibers.

Direct tensile test results indicate that the tensile strain capacities at peak stress (ε_{pc}) for UHP-FRCs reinforced with high-strength steel hooked fibers varied from roughly 0.3% to 0.6%, whereas those of UHP-FRCs containing high-strength steel straight smooth fibers ranged from 0.1% to 0.4%. The results suggest that using high-strength steel hooked fibers is a viable option that can enhance the tensile strain capacity of UHP-FRCs. Additionally, UHP-SIFCON reinforced with 7.5% hooked fibers showed 2.2-fold, 4-fold, 1.8-fold, and 6-fold increases in tensile strength, tensile strain capacity, compressive strength, and compressive strain capacity, respectively, compared to conventional UHP-FRCs reinforced with 3% straight smooth steel fibers.

5. Acknowledgements

The authors would like to express their gratitude to Byron Benson at Bekaert for donating the high-strength steel hooked fibers used in this study.

6. References

- AASHTO. *LRFD Bridge Design Specifications*. 9th edition, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2020.
- ACI Committee 318. *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318-19)*, American Concrete Institute, Farmington Hills, Michigan., 2019.
- Aghdasi, P., Heid A. E., and Chao, S.-H., "Developing Ultra-High-Performance Fiber-Reinforced Concrete for Large-Scale Structural Applications," *ACI Materials Journal*, V. 113, No. 5, September-October 2016, pp. 559-570.
- ASTM, *Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading*, ASTM C1609/C1609M, ASTM International, 2019.
- Naaman, A. E., *Fiber Reinforced Cement and Concrete Composites*. Techno Press 3000, 2017.
- Naaman, A. E. and Shah, S. P., "Strain Capacity of Strain-Hardening Ultra-High-Performance Concrete with Steel Fibers," *ACI Materials Journal*, V. 119, No. 2, March 2022, pp. 171-180.
- Qiu, M., Shao, X., Zhu, Y., Hussein, H. H., Li, F., and Li, X. "Effect of Aspect Ratios of Hooked End and Straight Steel Fibers on the Tensile Strength of UHPFRC," *ASCE Journal of Materials in Civil Engineering*, V. 34, No. 7, 2022, pp. 04022131-1 to 04022131-16.
- Wille, K. and Naaman, A. E., "Effect of Ultra-High-Performance Concrete on Pullout Behavior of High-Strength Brass-Coated Straight Steel Fibers," *ACI Materials Journal*, V. 110, No. 4, July-August 2013, pp. 451-461.