Innovations Deserving Exploratory Analysis Programs

IDEA

*NCHRP IDEA Program*

# High Bond Steel Fibers for Ultra High-Performance Concrete (UHPC)

Final Report for
NCHRP IDEA Project 235

Prepared by:
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HiPer Fiber, LLC

*September 2022*

TRANSPORTATION RESEARCH BOARD
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# High Bond Steel Fibers for Ultra High-Performance Concrete (UHPC)

**IDEA Program Final Report**

**Project Number**
NCHRP 20-30/IDEA 235

**Prepared for the IDEA Program**
**Transportation Research Board**
**The National Academies of Sciences, Engineering, and Medicine**

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Expert Advisory Panel:

- Mr. John Belcher, Bridge Construction Engineer, Michigan Department of Transportation
- Mr. Sam Fallaha, Richmond District Bridge Engineer, Virginia Department of Transportation
- Dr. Tom Fan, Houston District Bridge Engineer, Texas Department of Transportation
- Dr. Katrin Habel, Manager, Bridge Rehabilitation, Associated Engineering, Vancouver, Canada
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# EXECUTIVE SUMMARY

This project developed a novel type of steel fiber to reinforce ultrahigh performance concrete (UHPC) and demonstrated its use in a recently built bridge. The new fiber has micrometer-scale striations on its surface to ensure highly effective anchorage into the UHPC matrix. The initial research effort focused on identifying the optimal striation configuration and developing a viable technique to manufacture the fibers in commercial volume. An experimental testing program was then conducted to assess the effectiveness of the new surface modification technology. The experiments showed that the surface-modified fibers had a 130% increase in pullout resistance compared to non-modified fibers (i.e. more than double the capacity of the non-modified fibers). When used to reinforce UHPC at the traditional dosage of 2% by volume, the new fibers resulted in a 62% increase in strain at peak stress (the so-called localization strain) compared to specimens with non-modified fibers, i.e. it increased UHPC's ductility by close to two-thirds. When used at a reduced dosage of 1% by volume, i.e. half the regular dosage, the new fibers resulted in a performance that was on par with non-modified fibers at full 2% dosage.

Once the new fiber technology was perfected, a demonstration effort was undertaken to showcase its capabilities. The demonstration effort focused on the Bricker Road bridge over the Quackenbush Drain, which is owned by the St. Clair County Road Commission (a research partner). The bridge had a deteriorated reinforced concrete slab deck that was due for replacement. A set of replacement UHPC deck panels reinforced with the new fibers were designed and constructed. The UHPC panels were only about one third of the weight of the original reinforced concrete panels. Data collected during the project demonstrated that mixing the new fibers into the UHPC went smoothly and that the resulting field mix's spread was comparable to lab-mixed UHPC. Tension coupons and compression cube samples collected during the field trial showed that the field-mixed UHPC achieved mechanical properties that were just below the properties of lab-mixed UHPC, but still well above the design values.

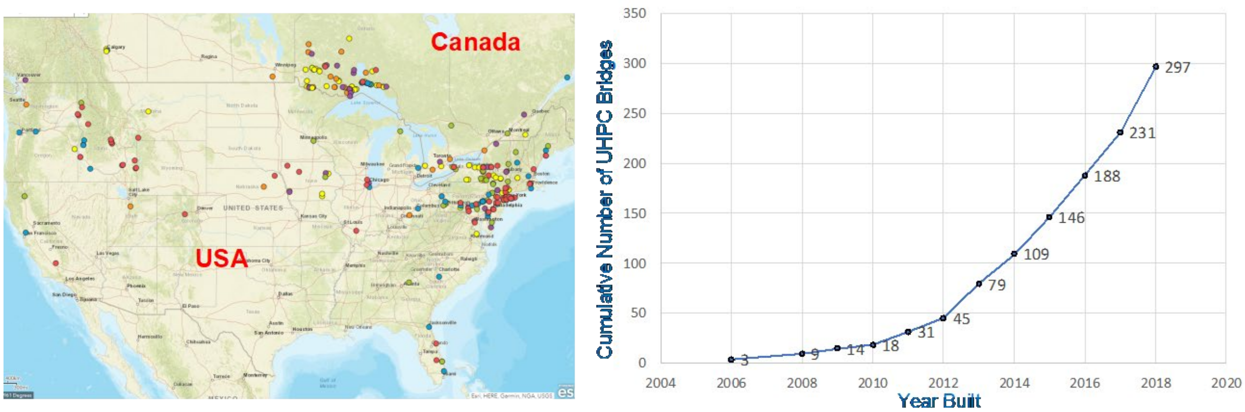
The demonstration bridge is the first bridge in the US in which the entire deck was made with open-recipe (non-proprietary) UHPC mixed in a traditional ready-mix truck. It decisively demonstrates the potential for using common concrete equipment for mixing UHPC. This paves the way for broader utilization of UHPC across the United State. The results of this project also indicate that by using the new steel fibers, it is feasible to reduce the dosage of steel fibers to 1% to 1.5% by volume from the traditional 2% by volume. Since steel fibers are the most expensive component of UHPC (accounting for up to 72% of the raw material cost), reducing fiber dosage this way will profoundly reduce the upfront cost of UHPC and hence broaden its appeal and usage.

**Striated Type X fiber developed in this project. Light reflection from the surface striations can be seen on the fibers.**

## INTRODUCTION AND MOTIVATION

Ultra-high performance concrete (UHPC) is a cementitious material that achieves a compressive strength of at least 21.7 ksi (150 MPa) and has self-consolidating properties (Graybeal 2006, 2008, 2014a, 2014b, Wille et al. 2011, 2012, 2014, 2016 and El-Tawil et al. 2016, 2019, 2020). It is comprised of component materials with particle sizes and distributions carefully selected to maximize packing density (Alkaysi et al. 2016, Alkaysi and El-Tawil 2016, 2017). The high packing density, which means that constituent particles are arranged as compactly as possible, is the reason for the extremely high mechanical and durability properties of the material (Pyo and El-Tawil 2013, 2015 and Pyo et al. 2014, 2016a, 2016b, Liu et al. 2018, Hung et al. 2021). Recognizing its potential, the Federal Highway Administration (FHWA) has aggressively promoted UHPC technology through its Everyday Counts (EDC) Programs 3, 4 and 6 spanning 2015 through 2022 (FHWA 2022a).

UHPC is no longer an experimental material and is rapidly going mainstream in the US (Graybeal 2006, 2008, 2014a, 2014b, Hung et al. 2021). The American Society of Testing and Materials (ASTM) and the American Concrete Institute (ACI) recently released guidelines for testing and designing structures made of UHPC (Saqif and El-Tawil 2022). Figure 1 shows the rapid growth of its use in bridges in the US and Canada (FHWA 2022b). The UHPC market was about $1B in 2016 and is projected to double by 2023 (GVR 2019). The projection was done before the passage of the Infrastructure Investment and Jobs Act that was recently signed into law by President Biden. That bill is poised to sharply accelerate usage of UHPC in the United States.




(a) Location of UHPC bridges in US and Canada

(b) Cumulative number of bridges per year

**FIGURE 1: Application of UHPC in US and Canadian bridge projects (FHWA 2022b)**

Steel fibers (see Figure 2) are a critical component of ultrahigh performance concrete (UHPC). They are added to give the material its characteristic strength, toughness and ductility (Tai et al. 2017, Tai and El-Tawil 2019a, 2019b, and Tai et al. 2020). Fibers are the most expensive component of UHPC and account for up to 72% of the raw material cost. Previous research has shown that the type of steel fiber most used in UHPC utilizes only 32% of each fiber's tensile capacity suggesting that the fibers are highly underutilized (El-Tawil et al. 2019). This is ironic given that the steel fibers represent the greatest cost investment in UHPC.

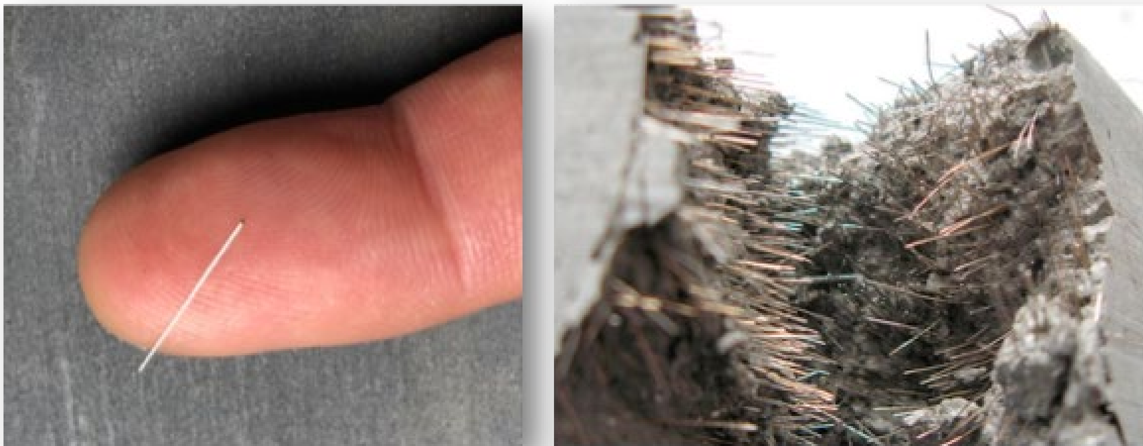


**FIGURE 2: Steel fibers are a critical component of UHPC**

## IDEA PRODUCT

HiPer Fiber, LLC, has invented a new type of steel fiber (named HiPer fiber, patent pending) that has the potential to triple the fibers' utilization rate, thus dramatically raising its efficiency and opening the door to substantial benefits. Unlike commonly used fibers that have a smooth surface, HiPer fibers have a striated surface to ensure highly effective anchorage into the UHPC matrix. The new fibers are not deformed and have a straight axis. Their advantage comes from the surface treatment. Therefore, they can be used in exactly the same way as current steel fibers. Contractors and precasters will be able to use them without requiring any special training for their mixing and pouring crews.

The premise of this project is that the high effectiveness of HiPer fiber will make the following assertions possible:

- A reduction in fiber dosage without compromising UHPC performance. Since steel fibers are the most expensive component of the raw material cost, a reduction in fiber dosage directly translates into a reduction in material cost. Making UHPC more affordable will increase its appeal and utilization in the construction industry.
- If the regular fiber dosage is maintained, the resulting UHPC will be capable of achieving substantially improved UHPC properties, specifically higher tensile strength and ductility.
- Since the pullout capacity is high, it is possible to transfer the same pullout force for a regular fiber using shorter HiPer fibers. Using shorter fibers is advantageous because it reduces mixing problems that occur at higher dosages.

## RESEARCH OBJECTIVES

This research effort systematically investigated the premises laid out above and demonstrated the use of the new type of fiber in an actual bridge construction project. The specific objectives were:

- Identify the most effective surface treatment for steel fibers and assess the feasibility and cost of producing a candidate fiber in commercial quantities.
- Construct a fiber production machine and manufacture the new fiber in sufficient quantities for the demonstration project.

- Conduct material testing to assess the effect of the new fibers on composite UHPC properties. The experimental variables were fiber type (smooth, Type A and Type X) and fiber dosage (which was 1%, 1.5%, 2% by volume) and the tests were conducted on tensile coupons, compression cubes and flexural prisms. Control testing was done with smooth steel fiber to ascertain the advantages of the proposed technology.
- Conduct a demonstration project on an actual bridge to showcase the potential of the new technology. The demonstration project was conducted in collaboration with the research partner, St. Clair County Road Commission (SCCRC).

## CONCEPT AND INNOVATION

### BACKGROUND

It is well established that the bond-slip relationship between fibers and the surrounding matrix directly influences the mechanical properties of the UHPC composite. Bond-slip response is activated when fibers bridge cracks that are trying to open further. The resistance they offer against crack opening promotes beneficial multiple cracking and enables strain hardening tensile behavior (Wille and Naaman 2012; Park et al. 2014; Tai et al. 2016). Optimal UHPC response is achieved by carefully tailoring the fiber-matrix bond characteristics. Too high of a bond force increases the tensile strength of UHPC but promotes early fiber breakage and leads to brittle behavior of the composite. Too low of a bond strength allows fibers to pull out easily, limiting their contribution to composite strength and toughness.

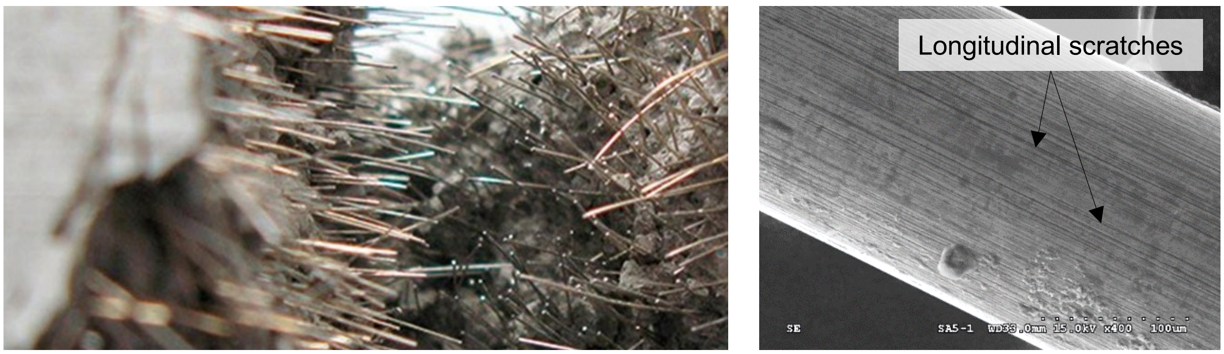
Bond-slip behavior depends on whether a fiber is straight or deformed. It has long been understood that fiber-matrix debonding and frictional sliding are the two primary resistance mechanisms governing the pullout behavior of straight fibers (Armelin and Banthia 1997). In addition to initial debonding and mechanical friction, deformed steel fibers mobilize mechanical anchorage during pullout. For example, hooked and twisted fibers tend to straighten and untwist, respectively, when pulled out (Tai and El-Tawil 2017). The mechanical anchorage part of deformed steel fibers has been the subject of numerous studies in the past (Alwan et al. 1999 and Sujivorakul et al. 2000). However, deformed fibers are substantially more expensive than undeformed fibers and are therefore rarely used in UHPC. Most UHPC users prefer straight steel fibers.

All the steel fibers that are available on the market and that have been investigated by various researchers have been smooth. Smooth fibers derive their resistance from chemical adhesion and friction. The former is quickly overcome as a fiber is pulled out, while the latter continues to provide resistance during pullout and is critical in ensuring strain hardening response. The fact that there are only limited studies of how fiber surface treatment can enhance the behavior of UHPC implies that there is a gap in knowledge that this effort sought to capitalize on.

### INNOVATION: STRIATED FIBERS

Steel fibers that are commonly used in UHPC are chopped from cold drawn wire. Research by the author has shown that the surrounding matrix scratches the fiber's surface during fiber pullout (see Figure 3). This scratching mechanism forms the basis of the frictional resistance to pullout. The frictional contribution creates a stress of 900 MPa in a 0.2 mm diameter by 13 mm long fiber, which is 32% of its tensile capacity (Tai and El-Tawil 2017). This means that the fibers, which are the most expensive component of UHPC, are not efficiently used.

The striated fibers developed by HiPer Fiber are optimized to boost the fiber-matrix interaction (trade named Type X). It is hypothesized that the shear keys that form due to the paste hardening in the surface striations supply the initial pull out resistance (Figure 4). After their initial resistance is overcome, the sheared keys continue to provide frictional resistance and supplement the native scratching mechanism shown in Figure 3b. They thus significantly boost the bond between the UHPC and steel fiber leading to better utilization of the fibers. HiPer fiber technology is patented by the University of Michigan and licensed exclusively to HiPer Fiber, LLC. Figure 5 shows Type X fibers produced as part of this project's effort. Light reflection from the surface striations can be seen on the fibers.




(a) Fiber pullout in a cracked UHPC structure

(b) SEM image of pulled out fiber showing scratches on surface.

**FIGURE 3: Steel fiber pullout during UHPC cracking**

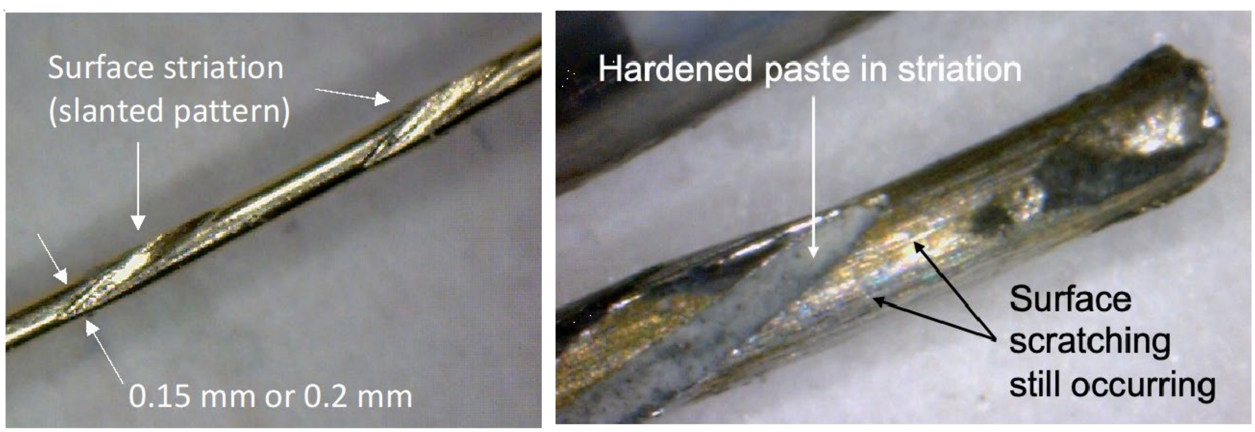



**FIGURE 4: Hardened paste in striation after pullout tests. Note that the scratches are still present on the fiber's surface.**

**FIGURE 5: Fiber production sample from new machine (new Type X fiber). Light reflection from the surface striations can be seen on the fibers**

## INVESTIGATION

An experimental testing program was conducted to explore the premise of this project that fibers with striated surfaces lead to substantially better UHPC performance and develop engineering data that could be used for bridge design purposes. Another key goal was to explore whether open-recipe UHPC made from off-the-shelf components (i.e. non-proprietary) could be prepared in a ready mix truck and to compare the properties of truck-mixed UHPC with lab-mixed UHPC.

### TEST PROGRAM

The author (along with his co-workers) developed a family of open recipe UHPC mixes made from common, off-the-shelf ingredients as outlined in Table 1 (El-Tawil et al. 2020). Mix D with the highest superplasticizer dose was used in this research effort. Table 2 shows the properties of the steel fibers used in this work. The workability of freshly mixed UHPC was determined by testing the spread value in accordance with ASTM C1437 (2015). The following mix protocol was used in both the lab and field mixes:

- Add the dry components and mix for ten minutes
- Mix the water and HRWR and then gradually add it to the mix over a 2 minute period
- Wait for turnover (fluidity), which usually occurs within five minutes
- Mix another five minutes after turnover
- Add fibers gradually over a 2-minute period
- Mix for five minutes then cast the specimens (coupons, cubes and prisms).

The specimens were left in the mold and covered for 24 hours then they were demolded and placed in a hot water bath (heated to 90 $^0$C) for 48 hours. Previous experience has shown that the UHPC specimens reach their full strength after this curing protocol (El-Tawil et al. 2020).

The pullout specimens were tested on an MTS 810 Material Test System (Figure 6). Figure 7 shows the type of results obtained from this test. The compression samples, which were (50mm × 50mm × 50mm) cubes, were tested on a Forney 1000 Series universal testing machine following Graybeal (2015) and as shown in Figure 8. Figure 9 shows typical results from the compression test. Tension tests were performed on 25mm × 25mm cross-section coupons (75mm gauge length) following Pyo et al. (2015, 2016) and Wille et al. (2014) with an MTS 810 Material Test System as shown in Figure 10. Figure 11 shows typical tensile results from the coupon tests. The flexural tests were conducted on 100mm × 100mm × 350mm prism specimens also using the MTS 810 Material Test System with a 55 kip (245 kN) actuator as shown in Figure 12. All test results are documented in Appendix I. Table 4 summarizes the compression test data, whereas Table 5 summarizes the test data.

TABLE 1: Mix Proportions by Weight for a Cubic Yard of UHPC

| Material (Weight in pounds) | | | | |
|---|---|---|---|---|
| Cement Blend | Mix A[1] | Mix B[1] | Mix C[1] | Mix D[1] |
| Ordinary Portland Type I | 653 | | | |
| Slag Cement (GGBS) | 653 | | | |
| Silica Sand | | | | |
| Fine Sand[2] | 398 | 396 | 395 | 394 |
| Coarse Sand[3] | 1590 | 1586 | 1582 | 1577 |
| Silica Fume | 327 | | | |
| Water | 276 | 272 | 268 | 264 |
| High Range Water Reducer[4,5] | 20 | 26 | 33 | 39 |
| Steel Fibers[6] | 265 | | | |

[1]Mixes A, B, C and D have HRWR dosages of 1.5%, 2%, 2.5% and 3%, respectively.

[2] Grain sizes: 80-200 microns

[3] Grain sizes 400-800 microns

[4] Polycarboxylate ether-based high range water reducer

[5] High range water reducer dosage rates can be adjusted to meet the paste flowability requirements, Dosages range vary with the type of silica fume and range from 1.5% to 3.0% by weight of the cement.

[6] The steel fibers are 2% by volume.

TABLE 2: Properties of Steel Fibers Used in this Study

| Type of Fiber | Density (kg/m$^3$) | Tensile Strength (MPa) | Length of Fiber $l_f$ (mm) | Diameter of Fiber $d_f$ (mm) | Fiber Aspect Ratio $l_f/d_f$ |
|---|---|---|---|---|---|
| Straight, Brass Coated | 7800.0 | >2800 | 13.0 | 0.20 | 65.0 |

Table 3 shows the matrix of tests conducted in this work. A total of 24 pull out tests, 45 compression cubes, 90 tensile coupons, and 45 flexural prisms were tested in this program. The main variables were the fiber type (smooth, Type A and Type X), fiber dosage (1%, 1.5% and 2% by volume) and fiber blend (20% Type X/80% Type A and 40% Type X/60% Type A). Type A is also produced by HiPer Fiber, LLC. It has some surface markings due to the production process, but it does not include deliberate striations with optimal patterns as Type X does. Since Type A is somewhat cheaper to produce than Type X, blending them could result in a cheaper overall product than Type X, but that still has some of the key characteristics of Type X.

## EFFECT OF STRIATIONS ON PULLOUT CAPACITY

Figure 6 shows the test setup for the pullout experiments. UHPC specimens were cast with a single fiber precisely embedded in them. Each specimen was placed in the test rig and the fiber clamped by the test machine as close as possible to the UHPC specimen's top surface to prevent fiber elongation from affecting the results. The fibers were then pulled out at the rate of 0.018 mm/sec. The pullout force and displacement were recorded for each experiment and the full set of test results are shown in Appendix 1 (Figure 26). The light grey lines in the plots represent individual test data while the heavy lines represent the average. A direct comparison that shows the benefits of the surface treatment can be seen in Figure 7, where its clear that the pullout resistance of Type X fibers (44N) is 230% of that for smooth fibers (19N), i.e. more than double.

TABLE 3: Matrix of Tests

**HiPer Fiber Test Program**

**Smooth**

| Fiber volume fraction | Pullout tests | Compression test (2x2x2" cube) | Direct Tensile test (coupon) | Flexural test |
|---|---|---|---|---|
| 1 | 8 | 3 | 6 | 3 |
| 1.5 | | 3 | 6 | 3 |
| 2 | | 3 | 6 | 3 |

**TYPE-A**

| Fiber volume fraction | Pullout tests | Compression test (2x2x2" cube) | Direct Tensile test (coupon) | Flexural test |
|---|---|---|---|---|
| 1 | 8 | 3 | 6 | 3 |
| 1.5 | | 3 | 6 | 3 |
| 2 | | 3 | 6 | 3 |

**TYPE-X**

| Fiber volume fraction | Pullout tests | Compression test (2x2x2" cube) | Direct Tensile test (coupon) | Flexural test |
|---|---|---|---|---|
| 1 | 8 | 3 | 6 | 3 |
| 1.5 | | 3 | 6 | 3 |
| 2 | | 3 | 6 | 3 |

**BLEND-20X80A**

| Fiber volume fraction | Compression test (2x2x2" cube) | Direct Tensile test (coupon) | Flexural test |
|---|---|---|---|
| 1 | 3 | 6 | 3 |
| 1.5 | 3 | 6 | 3 |
| 2 | 3 | 6 | 3 |

**BLEND-40X60A**

| Fiber volume fraction | Compression test (2x2x2" cube) | Direct Tensile test (coupon) | Flexural test |
|---|---|---|---|
| 1 | 3 | 6 | 3 |
| 1.5 | 3 | 6 | 3 |
| 2 | 3 | 6 | 3 |

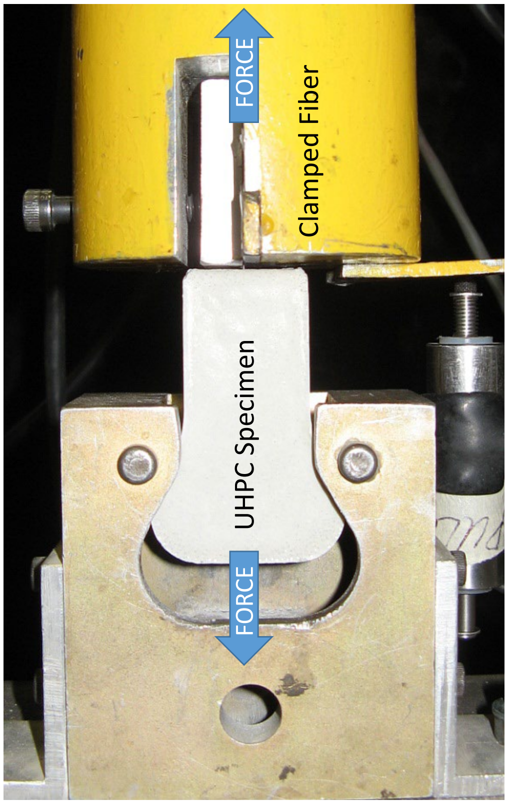



**FIGURE 6: Pull out test configuration**

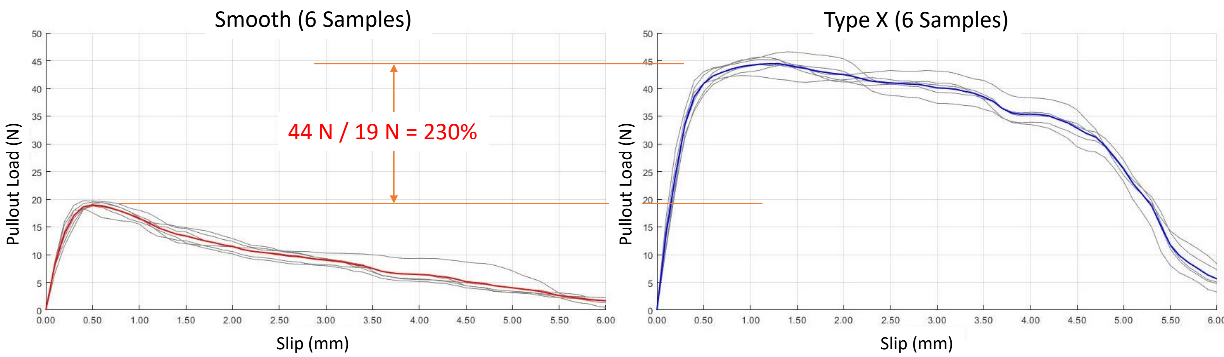



**FIGURE 7: Benefit of Type X in pull out**

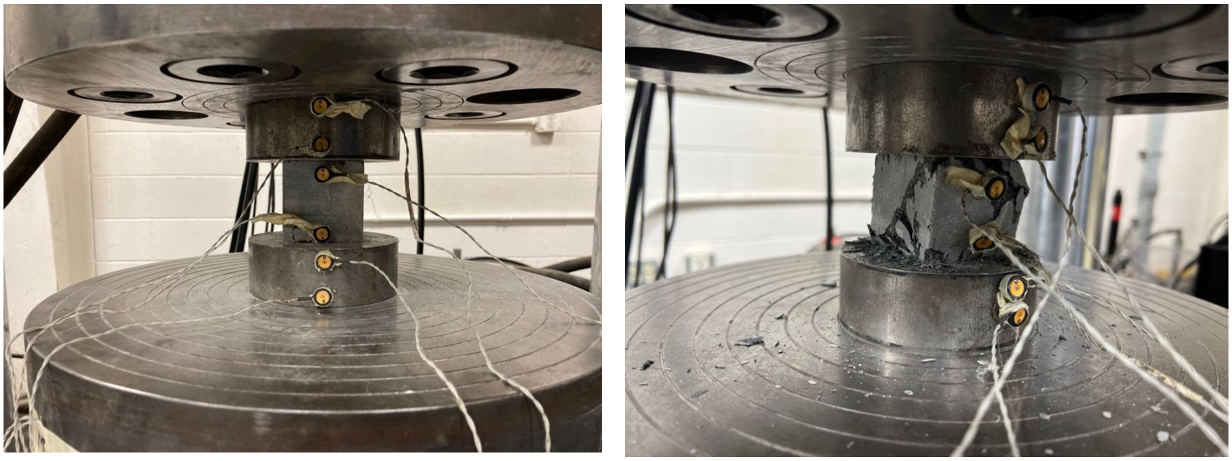


**FIGURE 8: Compressive test setup**

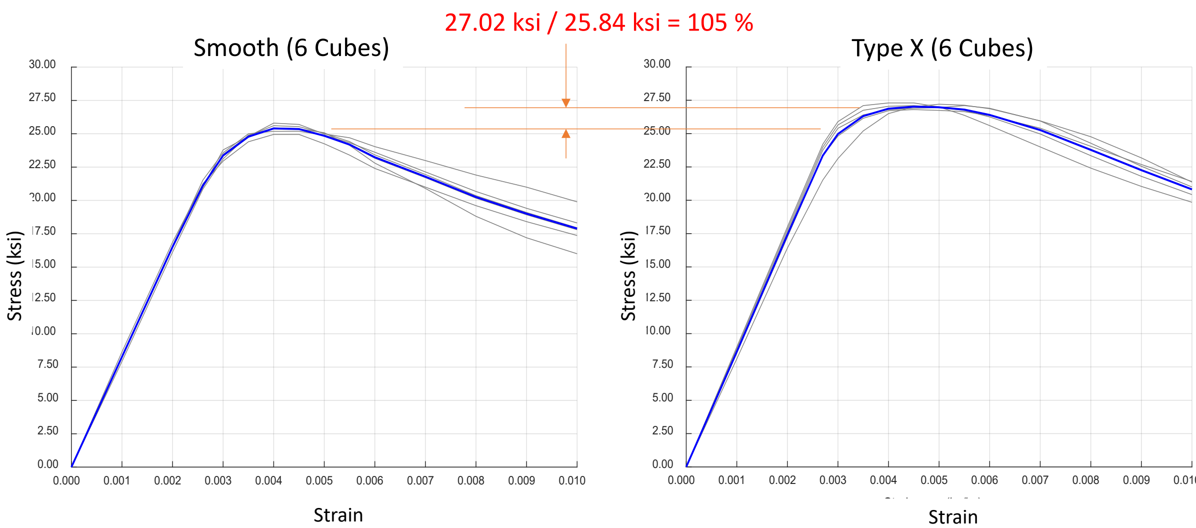



**FIGURE 9: Benefit of Type X in compression**

## ANALYSIS OF TEST RESULTS

The striations on Type X fibers not only increased the pullout capacity of an individual fiber, they also positively influenced the mechanical properties of the UHPC composite. The effect on compressive capacity was mild. As shown in Figure 9, specimens with Type X fibers caused only a 5% increase in compressive capacity compared to specimens with smooth fibers. However, the softening curve was shallower, reflecting the greater ability of the fibers to ‘hold’ the specimen together. These observations were expected since the fibers are designed to target the tensile properties of the material.

The true benefit of the striations can be seen in Figure 11. Although the fibers caused only a mild increase in tensile strength over the smooth fibers (5%), they resulted in a 62% increase in the localization strain at 2% by volume dosage. This represents a significant increase in the performance of the material. The performance increase is generally quite high as can be seen by comparing the localization strains in Table 5 at different fiber dosages. For example, smooth fibers at 2% dosage have a localization strain of 0.26%. Type X fibers at 1%, 1.5% and 2% have localization strains of 0.23%, 0.30% and 0.42%, respectively. These numbers suggest that Type X at 1% dosage (localization strain of 0.23%) has comparable localization strain performance to smooth fibers at 2% dosage (0.26% localization strain). This represents a huge reduction in the cost of the steel fibers used to reinforce UHPC and, since steel fibers are the most expensive component of UHPC, will lead to a commensurate reduction in UHPC cost.

The flexural data shows similar trends. For example, at 2% dosage, the flexural tensile strength of Type X specimens is 21% higher than smooth fibers and caused a 62% increase in the deflection at peak load (Figure 13). At 1.5% dosage (see Figure 28 in the Appendix), the Type X beams had about the same deflection as the smooth fibers at 2% dosage (see Figure 29 in the Appendix), but exhibited a generally lower strength.

**TYPE A VERSUS TYPE X AND TYPE A/X BLENDS**

Further analysis of the test results shows that Type A fibers have substantially better response than smooth fibers, but lower performance than Type X. For example, at 2% dosage, Type A fibers have a localization strain that is 38% more than that for smooth fibers at the same dosage (compare that to 62% for Type X). The blended fiber types had responses that were in between the response of Type A and Type X fibers.

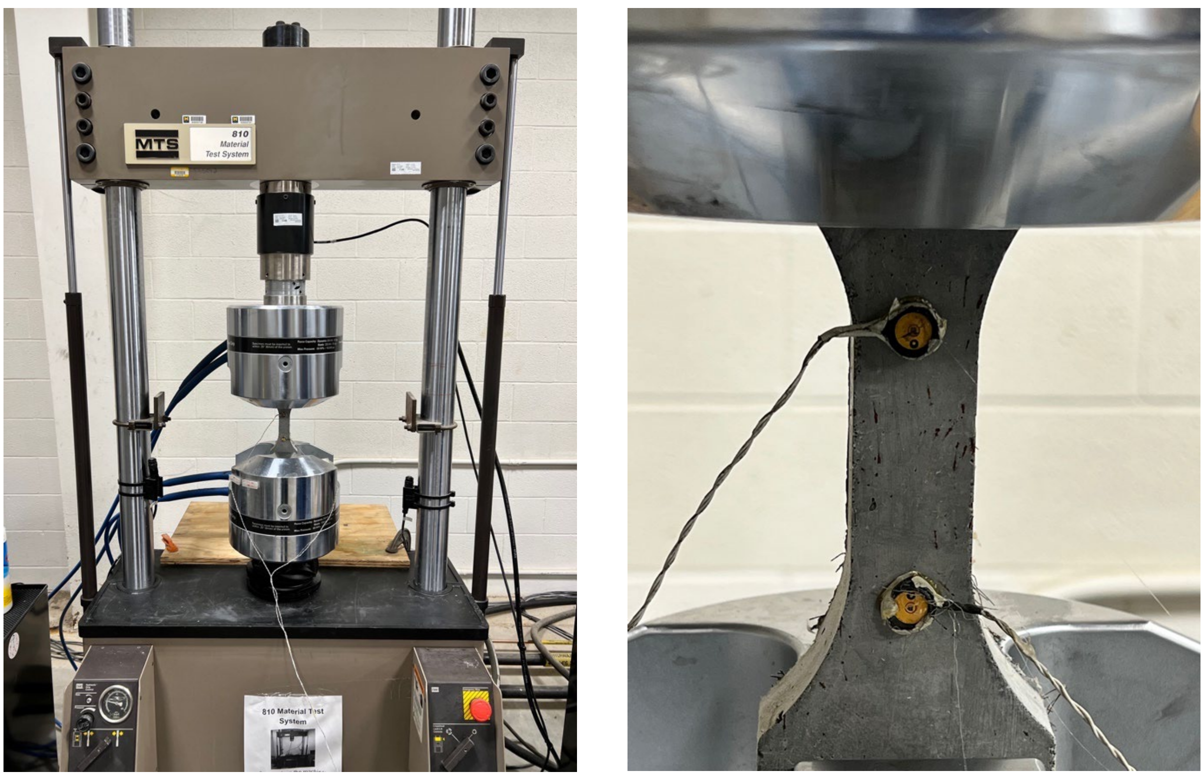



**FIGURE 10: Tensile test configuration**

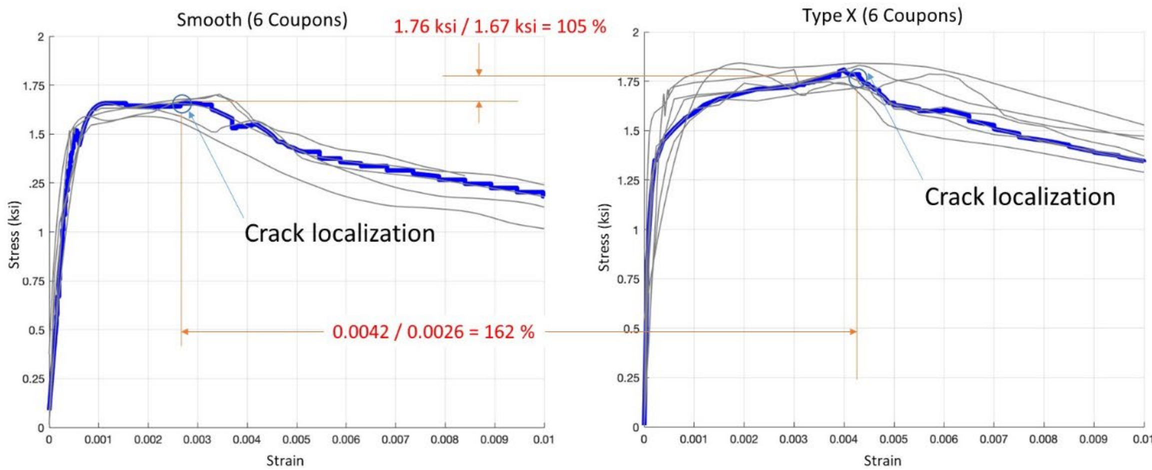



**FIGURE 11: Benefit of Type X in tension**

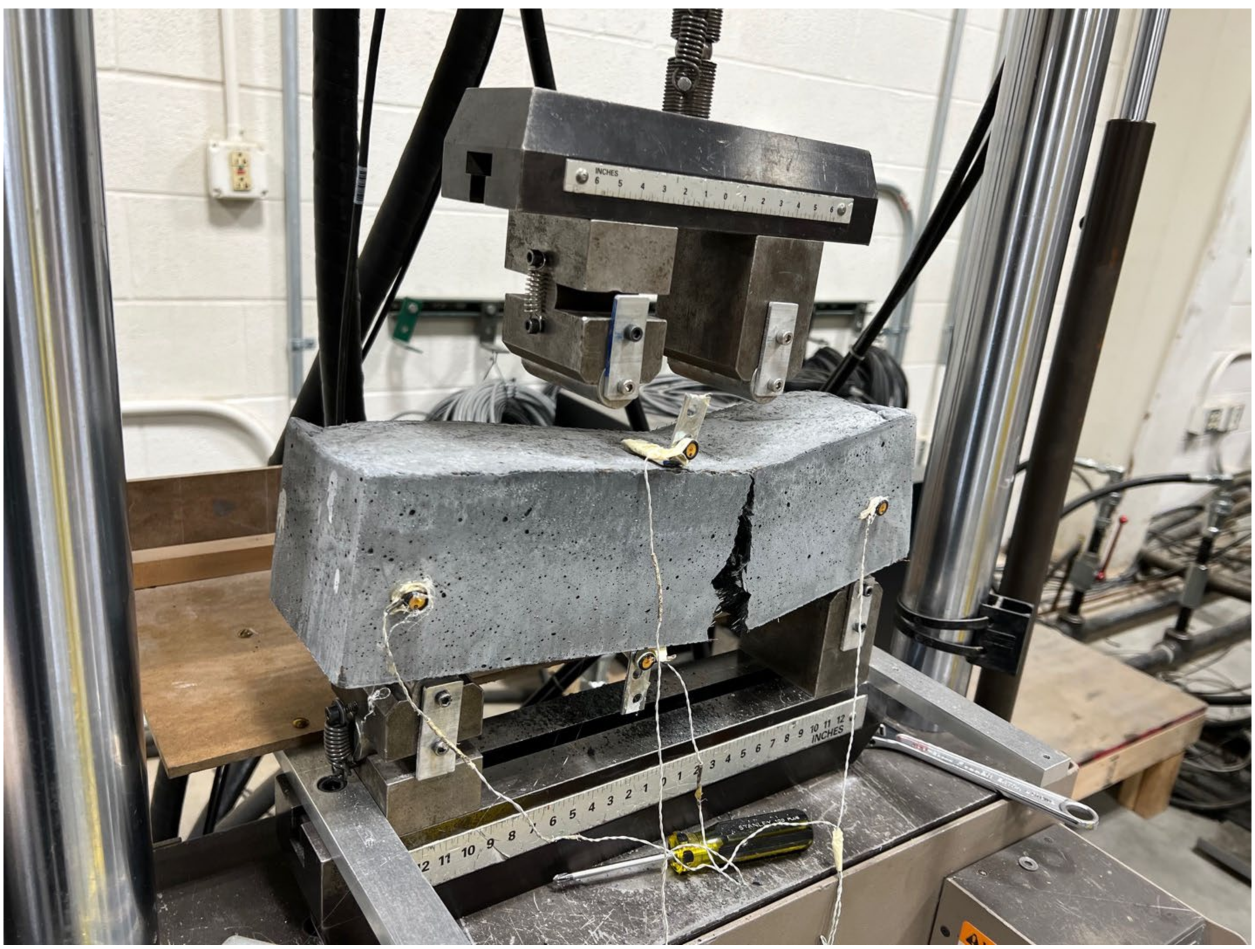



**FIGURE 12: Flexural test setup**

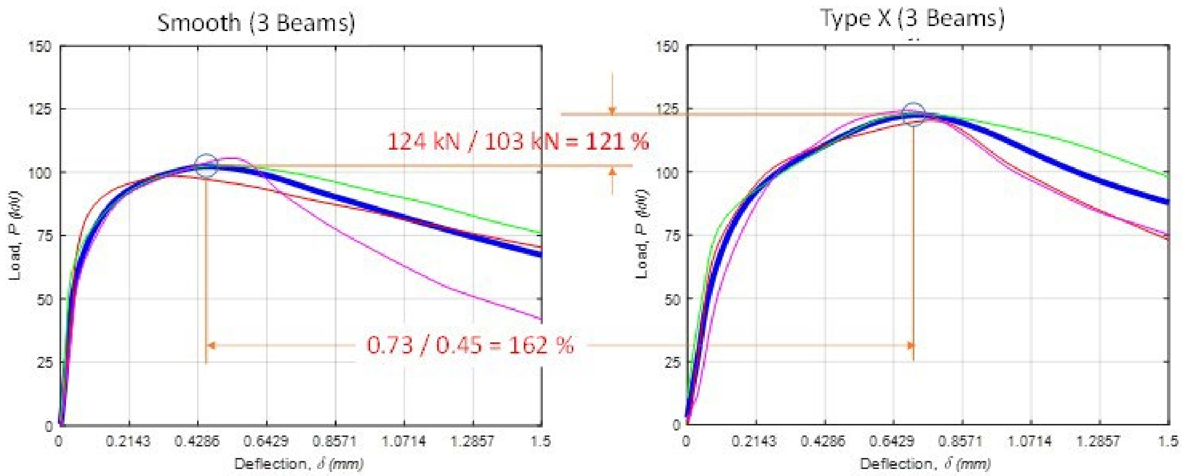



**FIGURE 13: Benefit of Type X in flexure**

TABLE 4: Summary of Compressive Test Data

| Fiber | Fiber volume fraction | Elastic compression strain limit | Elastic modulus | Ultimate compressive strain | Compressive Strength |
|---|---|---|---|---|---|
| | $V_f$ (%) | $\varepsilon_{cp}$ (in./in.) | $E_c$ (ksi) | $\varepsilon_{cu}$ (in./in.) | $f'_c$ (ksi) |
| Type A | 1.0 | 0.0023 | 6404 | 0.0028 | 18.08 |
| | 1.5 | 0.0029 | 6521 | 0.0041 | 21.79 |
| | 2.0 | 0.0028 | 7714 | 0.0052 | 26.71 |
| Type X | 1.0 | 0.0025 | 6589 | 0.0031 | 19.14 |
| | 1.5 | 0.0026 | 7115 | 0.0045 | 22.01 |
| | 2.0 | 0.0027 | 8232 | 0.0055 | 27.02 |
| Blend A80-20X | 1.0 | 0.0023 | 6720 | 0.0028 | 18.44 |
| | 1.5 | 0.0030 | 6333 | 0.0040 | 21.61 |
| | 2.0 | 0.0030 | 7989 | 0.0050 | 26.55 |
| Blend A60-40X | 1.0 | 0.0025 | 6456 | 0.0030 | 18.62 |
| | 1.5 | 0.0030 | 6895 | 0.0044 | 22.07 |
| | 2.0 | 0.0028 | 8207 | 0.0053 | 27.07 |
| Smooth | 1.0 | 0.0020 | 6365 | 0.0027 | 16.23 |
| | 1.5 | 0.0030 | 6350 | 0.0038 | 20.49 |
| | 2.0 | 0.0026 | 7818 | 0.0046 | 25.84 |

TABLE 5: Summary of Tensile Test Data

| Fiber | Fiber volume fraction | First cracking strain | First cracking Stress | Elastic modulus | Localization strain | Tensile strength |
|---|---|---|---|---|---|---|
| | $V_f$ (%) | $\varepsilon_{cr}$ (in./in.) | $f_{cr}$ (ksi) | $E_c$ (ksi) | $\varepsilon_t$ (in./in.) | $f_t$ (ksi) |
| Type A | 1.0 | 0.00019 | 1.10 | 5801 | 0.0018 | 1.17 |
| | 1.5 | 0.00019 | 1.18 | 6210 | 0.0028 | 1.31 |
| | 2.0 | 0.00019 | 1.46 | 7684 | 0.0036 | 1.67 |
| Type X | 1.0 | 0.00018 | 1.09 | 5956 | 0.0023 | 1.18 |
| | 1.5 | 0.00019 | 1.23 | 6648 | 0.0030 | 1.35 |
| | 2.0 | 0.00017 | 1.52 | 8786 | 0.0042 | 1.79 |
| Blend A80-20X | 1.0 | 0.00019 | 1.11 | 5842 | 0.0018 | 1.18 |
| | 1.5 | 0.00019 | 1.21 | 6309 | 0.0029 | 1.35 |
| | 2.0 | 0.00019 | 1.43 | 7526 | 0.0035 | 1.69 |
| Blend A60-40X | 1.0 | 0.00019 | 1.09 | 5831 | 0.0021 | 1.19 |
| | 1.5 | 0.00018 | 1.19 | 6611 | 0.0031 | 1.33 |
| | 2.0 | 0.00018 | 1.44 | 7795 | 0.0042 | 1.74 |
| Smooth | 1.0 | 0.00018 | 1.02 | 5679 | 0.0016 | 1.09 |
| | 1.5 | 0.00020 | 1.19 | 5872 | 0.0022 | 1.28 |
| | 2.0 | 0.00020 | 1.48 | 7081 | 0.0026 | 1.66 |

## IMPLEMENTATION

### A SMALL BRIDGE WITH BIG IMPLICATIONS!

A bridge construction demonstration project was undertaken to showcase the developed technology. The bridge, named Bricker Road Bridge over the Quackenbush Drain, is owned by the St. Clair County Road Commission, which was a research partner. Figure 14 shows the project's location. A UHPC bridge deck was proposed and designed to replace an existing deteriorated reinforced concrete deck. Figure 15 shows the general plans for the bridge. The entire bridge deck was made of open-recipe UHPC with HiPer Fiber Type X steel fibers. The replacement bridge was designed by the bridge design firm, TEGcivil Engineering, LLC, of Wyoming, MI. Although small with a span of only 22 ft, this bridge represents a big step forward in UHPC technology. To the knowledge of the author, it is the first bridge in the US to have its entire deck made of open-recipe UHPC mixed on-site in a traditional ready-mix truck.

### BRIDGE DETAILS

The replacement bridge comprised six ribbed panels, each six feet wide for a total width of 36 feet (Figure 16). Each panel had 3" deck with 10.5" deep ribs (see Figure 17). Once the panels were installed, the closure pours were filled with UHPC that was truck mixed on site. The weight saving over the 16-inch traditional deck was about two thirds. The bridge features a long span guard rail so as not to attach the rail to the thin decks.

## ANALYSIS AND DESIGN

The design of the bridge was conducted according to the AASHTO Bridge Design Specifications (2018) and the draft specifications proposed by FHWA and ACI Committee 239 (FHWA-UHPC, 2022) for incorporation into the AASHTO bridge design specifications. As discussed later and shown in Figure 18, the field-measured parameters exceeded those used in design, implying that the design is conservative. Figure 17 shows the rebars arrangement. The bars were necessary to ensure sufficient flexural strength. However, no stirrups were used for shear reinforcement as the shear computations showed adequate shear strength compared to the demand. The stirrups shown in Figure 17 were used to facilitate bar placement.

In addition to strength design computations, a moment curvature analysis was conducted to ascertain moment strength. Figure 19 shows the idealized stress strain curves based on the nominal design properties, whereas Figure 20 shows the moment curvature response of the cross-section that was computed using the nominal design properties and idealized stress strain curves. The flexural strength computed from the moment-curvature analysis was in accord with the design values.

### Bridge Construction

The UHPC for each panel was mixed at a precasting plant in a typical commercial ready-mix truck. Slump testing of the mixture was watched and tracked with the onboard flow meter in the ready-mix truck. Previously mixed and placed material was used as a guide to when the material was ready for placement. The flow meter on the ready-mix truck had a reading of 1100 which equated to approximately 8.5” spread. Placement was not started until an 1100 reading was measured. After casting, the panels were left in their forms for the first 24 hours with wet burlap and visqueen covering them. After the panels were removed from the forms, the planks were wet cured with burlap and visqueen an additional 6 days. Given the rather high temperatures observed during mixing, a large amount of ice was added to the water to help cool the mixture. Past experience has shown that UHPC will start curing prematurely in temperatures above 80 degrees Fahrenheit.

Table 6 shows the results of laboratory testing of the field-cast compression cubes arranged by mix date. Samples were not collected from the very first mix due to a mix-up in the field. Compression testing was done by a third party. Table 6 also shows the progression of strength gain with time. Initial strength gain was rapid, with the compression strength reaching 15.1 ksi in 3 days. The rate slowed down substantially after that and the average strength across all mixes eventually reached 23.9 ksi, with the lowest strength being 23.4 ksi. As noted earlier, the measured values are all above the design values.

Figure 22 shows tensile testing data from field-cast coupons (similar in size to the lab speicmens). The coupons considered were compiled from three mixes due to limitations in the number of available molds and because several specimens did not fail in the gage length as shown in Figure 21. The coupons were cast by on site construction workers without experience in casting tensile coupon specimens. Nevertheless, the results show a localization strain of 0.48%, which is on par with the experimentally measured one (0.42%). The peak tensile stress of 1.42 ksi was 21% below the experimental one of 1.79 ksi, but still more than the design value of 1.15 ksi. Another observation is that the variability is higher than in the lab-tested coupons, but that could be attributed to the fact that the data came from three separate mixes.

Figure 23 shows details of the construction process. The bridge opened to the public in September 2022 after load testing. Figure 24 and Figure 25 show details of the finalized bridge.

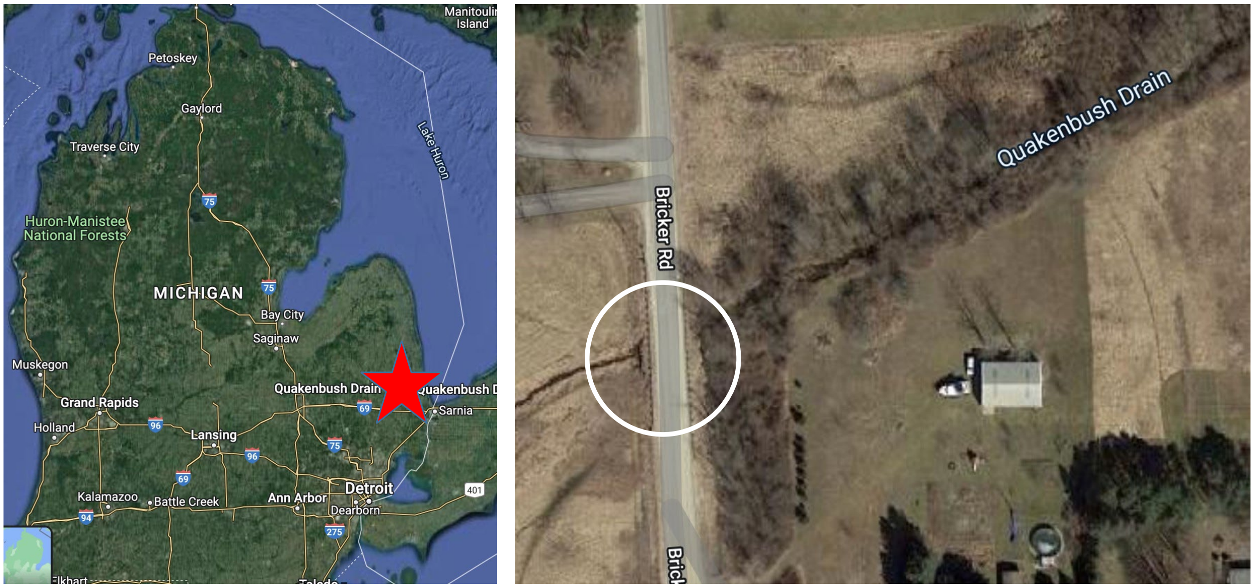



**FIGURE 14: Demonstration bridge location**

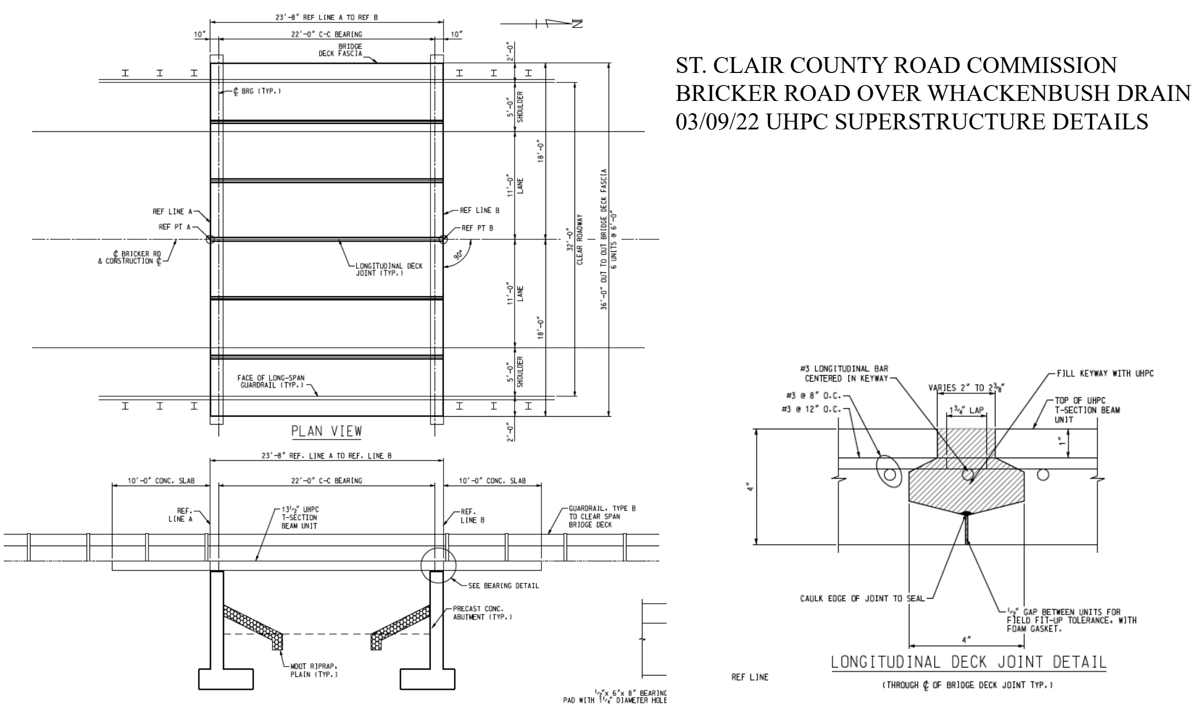



**FIGURE 15: General bridge plans for the demonstration project**

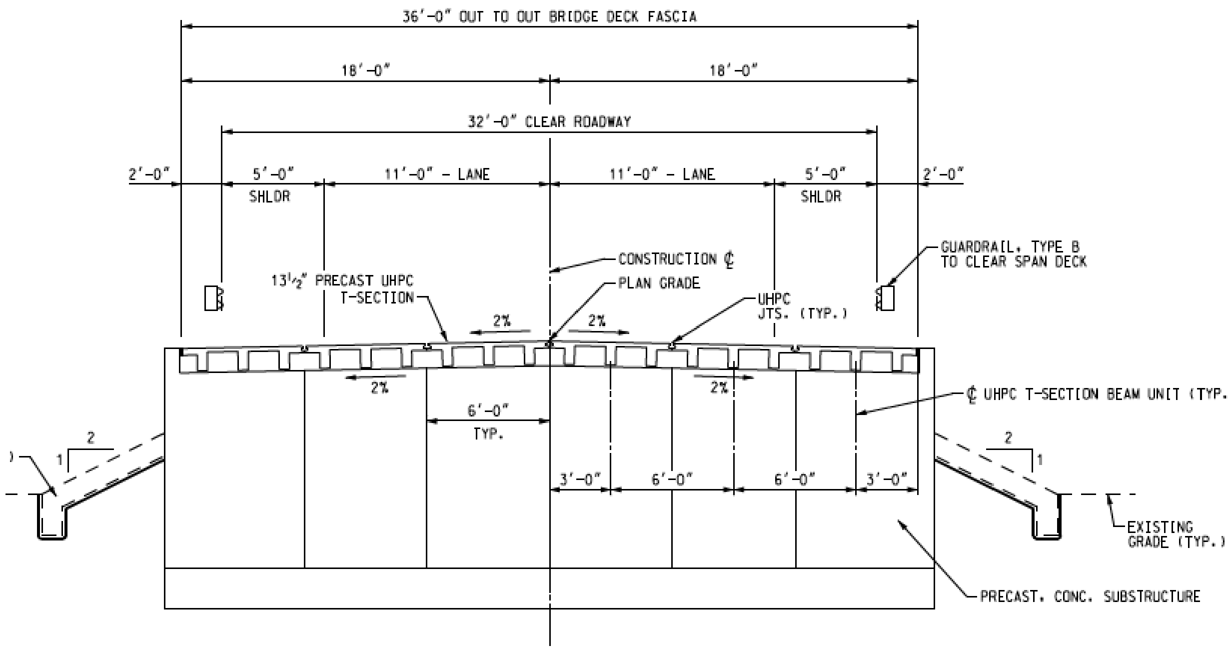



**FIGURE 16: Bridge cross-section**

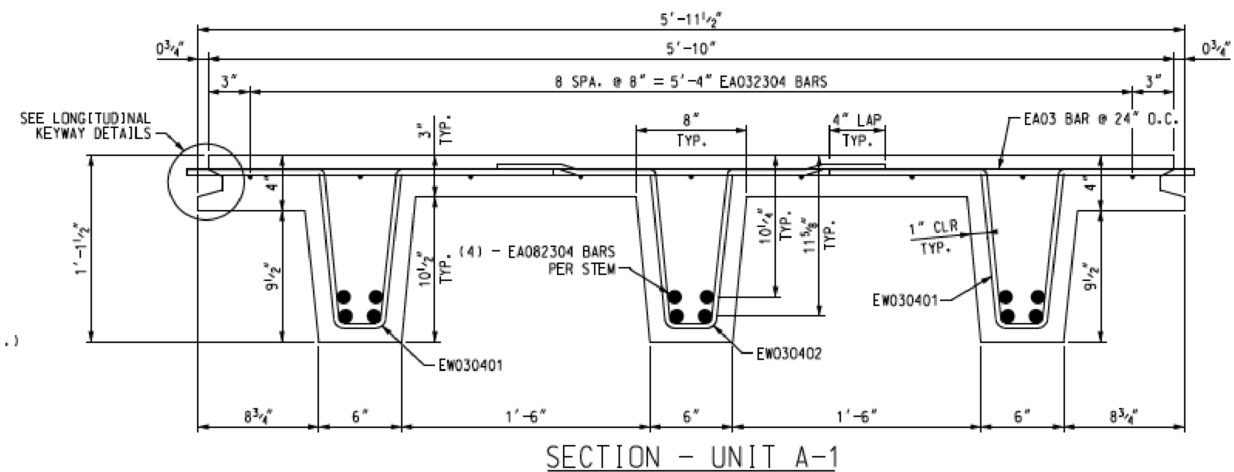



**FIGURE 17: Individual panel cross-section**

| Design Parameters | Actual Parameters From Test Data |
|---|---|
| $f_c'$=21.5 ksi | $f_c'$=23.9 ksi |
| $\varepsilon_{cu}$=0.004 | $\varepsilon_{cu}$=0.005 |
| E=7500 ksi | E=8750 ksi |
| $f_t$=1.15 ksi | $f_t$=1.42 ksi |
| $\varepsilon_{t,loc}$=0.0025 | $\varepsilon_{t,loc}$=0.005 |
| $f_y$=60ksi | $f_y$=60ksi |

**FIGURE 18: Design parameters versus measured parameters for the demonstration bridge.**

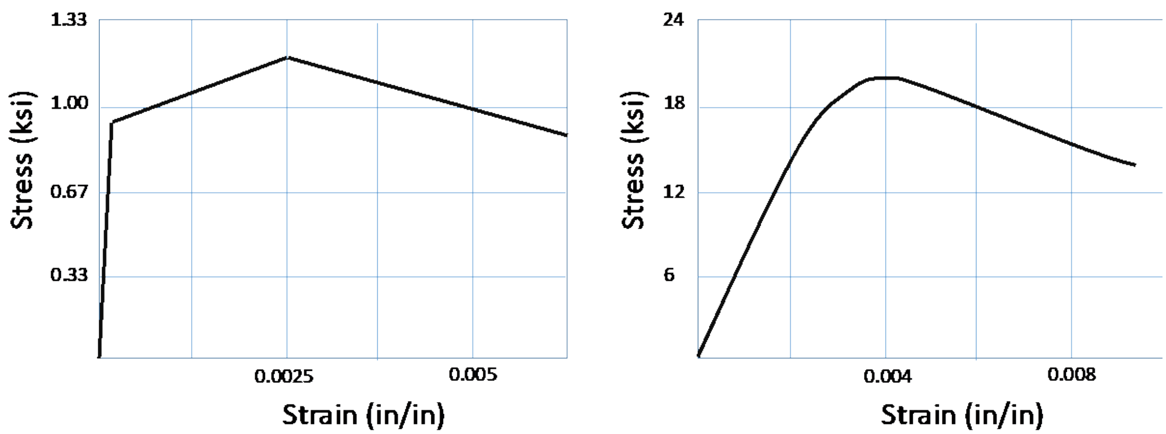



**FIGURE 19: Idealized stress-strain curves used to compute moment-curvature analysis**

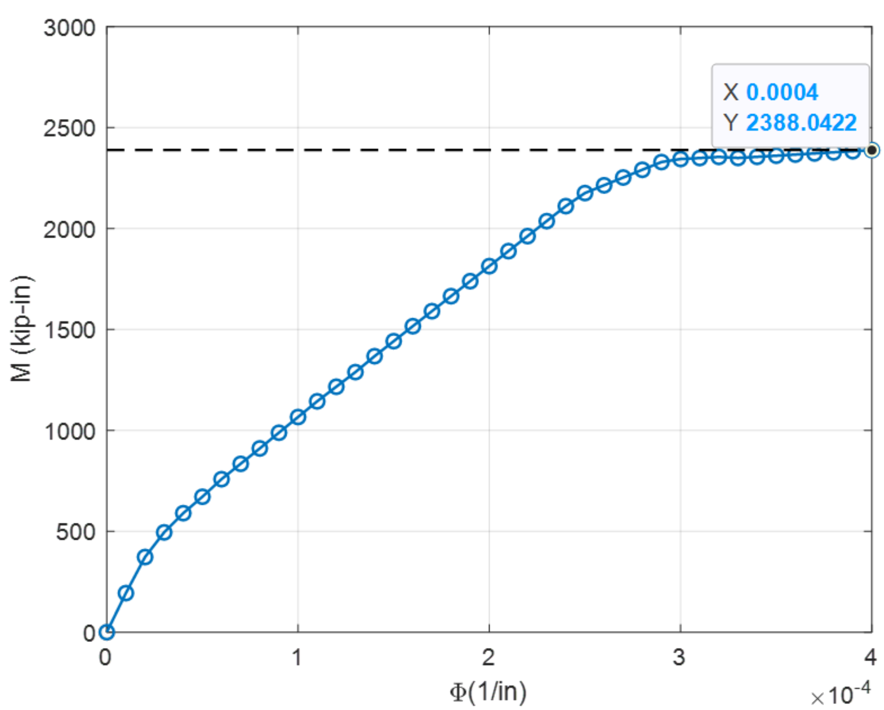



**FIGURE 20: Moment curvature response of UHPC cross-section**

TABLE 6: Compression Strength (ksi) of Samples at Different Intervals for Various Mixes

| Pour Date | Curing Time (days) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3 | 4 | 5 | 7 | 10 | 11 | 14 | 28 |
| 12-Jul | 15.1 | | | 20.2 | | | | 25.0 |
| 14-Jul | | | 16.7 | 20.6 | | | | 23.4 |
| 15-Jul | | 17.6 | | | 20.7 | | | 23.5 |
| 18-Jul | | | | | | 19.1 | 20.2 | 24.1 |
| 19-Jul | | | | | 18.9 | | 22.4 | 23.7 |
| Average | 15.1 | 17.6 | 16.7 | 20.4 | 19.8 | 19.1 | 21.3 | 23.9 |


**FIGURE 21: Field cast tensile coupons. Curves in Figure 21 are from specimens marked with a star, which are ones that failed in the gage length. NOTE: Specimens were made by field staff with no experience in collecting tensile samples**

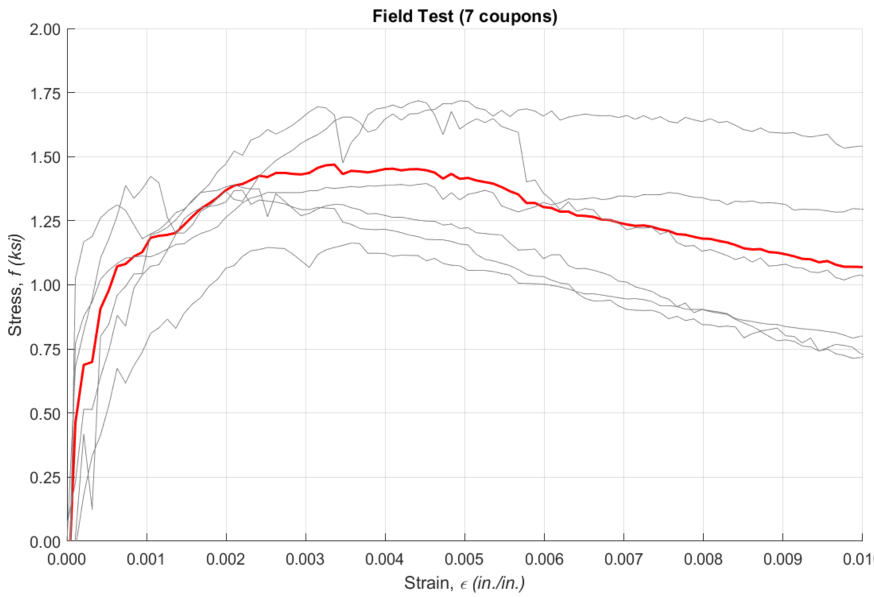
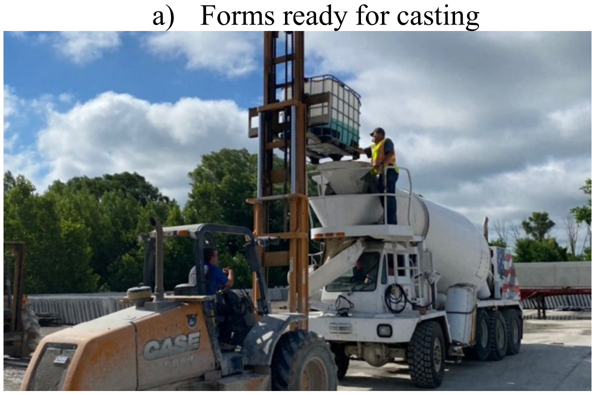



**FIGURE 22: Tensile test results of field cast coupon. Red curve is the average of the measured response.**

a) Forms ready for casting

b) Loading of sand into ready-mix truck



c) Loading of water and water reducer

d) Loading steel fibers

e) Casting of UHPC materials in form

f) Casting of UHPC materials in form

g) Finished panel

h) Wrapped and curing panel

i) Closure pours

**FIGURE 23: Construction process of the UHPC deck (pictures courtesy of William Hazelton)**

**FIGURE 24: Close up of bridge superstructure (picture courtesy of William Hazelton)**

**FIGURE 25: Profile of bridge superstructure (picture courtesy of William Hazelton)**

## CONCLUSIONS

This project developed a novel type of steel fiber to reinforce ultrahigh performance concrete (UHPC) and demonstrated its use in a recently built bridge. The new fiber has micrometer-scale striations on its surface to ensure highly effective anchorage into the UHPC matrix. The initial research effort focused on identifying the optimal striation configuration and developing a viable technique to manufacture the fibers in commercial volume. Once the new fiber technology was perfected, a demonstration effort was undertaken to showcase the new fiber's capabilities. The demonstration effort focused on the Bricker Road bridge over the Quackenbush Drain, which is owned by the St. Clair County Road Commission (a research partner). The bridge had a deteriorated reinforced concrete slab deck that was due for replacement. A set of replacement UHPC deck panels reinforced with the new fibers were designed, constructed and installed. The UHPC panels were only about one third of the weight of the original reinforced concrete panels.

The main conclusions that can be drawn from this research are as follows:

- Surface striations are highly effective in boosting fiber performance. Pullout experiments showed that the surface-modified fibers (Type X) had a 130% increase in pullout resistance compared to non-modified fibers (i.e. more than double). When used to reinforce UHPC at the traditional dosage of 2% by volume, the new fibers resulted in a 62% increase in strain at peak stress (the so-called localization strain) compared to specimens with non-modified fibers, i.e it increased UHPC's ductility by close to two-thirds. When used at a reduced dosage of 1% by volume, i.e. half the regular dosage, the new fibers resulted in a localization strain that was on par with non-modified fibers at full dosage.

- Type A fibers have substantially better response than smooth fibers, but lower performance than Type X. Type A is also produced by HiPer Fiber, LLC. It has some surface markings due to the production process, but it does not include deliberate striations with optimal patterns as Type X does. For example, at 2% dosage, Type A fibers have a localization strain that is 38% more than that for smooth fibers at the same dosage (compare that to 62% for Type X). The blended fiber types had responses that were in between the response of Type A and Type X fibers.

- Data collected during the project demonstrated that mixing the new fibers into the UHPC went smoothly and that the resulting mix's spread was comparable to traditional mixes. Tension coupon and compression cube samples collected during the field trial showed that the field-mixed UHPC achieved mechanical properties that were just below the properties of lab-mixed UHPC, but still well above the design values.

The demonstration bridge is the first bridge in the US in which the entire deck is made with open-recipe UHPC mixed in a traditional ready-mix truck. It clearly demonstrates the potential for using common concrete equipment for mixing UHPC. This paves the way for broader utilization of UHPC across the United State. The results of this project also indicate that by using the new steel fibers, it is feasible to reduce the dosage of steel fibers to 1% to 1.5% by volume from the traditional 2% by volume. Since steel fibers are the most expensive component of UHPC (accounting for up to 72% of the raw material cost), reducing fiber dosage this way will profoundly reduce the upfront cost of UHPC and hence broaden its appeal and usage. Since UHPC is several times as durable as regular concrete, building our national transportation system from this unique material will not only be an overall greener solution, but also lead to substantial long-term savings due to the extremely low life cycle cost of UHPC components.

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## APPENDIX I: TEST DATA

All data from the test program is provided in this Appendix.

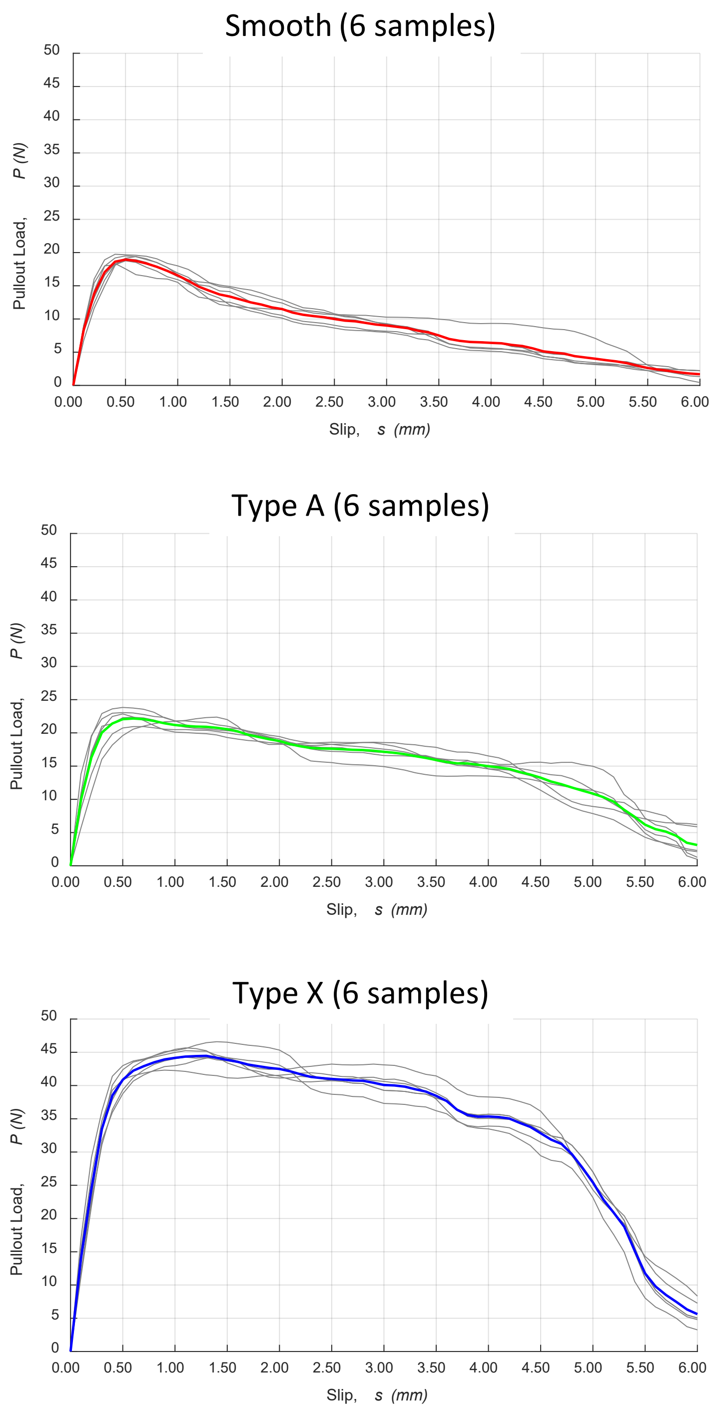


**FIGURE 26: Pull out test data**

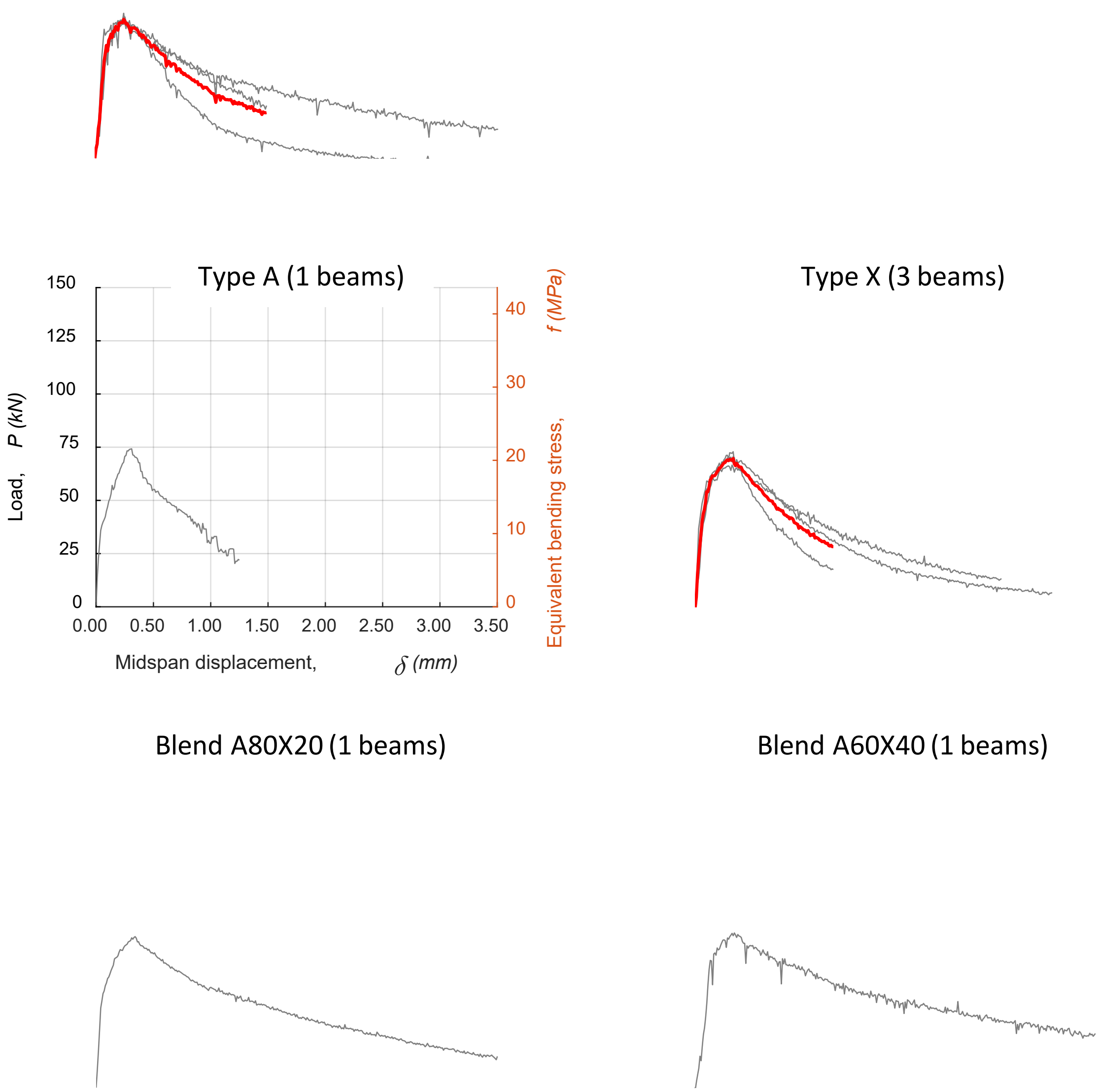


**FIGURE 27: Flexural tests (steel fiber $V_f$ = 1%)**

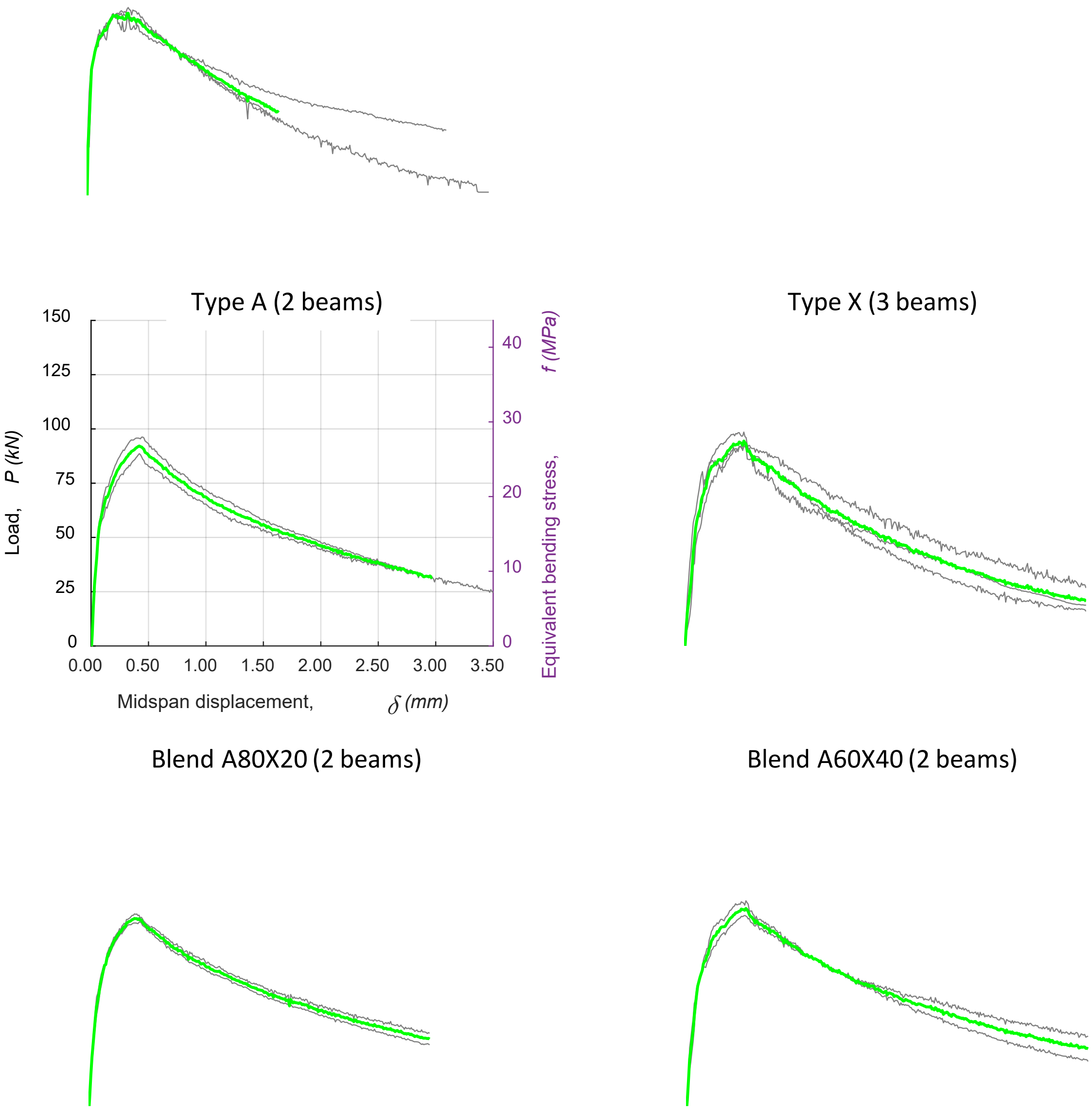


**FIGURE 28: Flexural tests (steel fiber $V_f$ = 1.5%)**

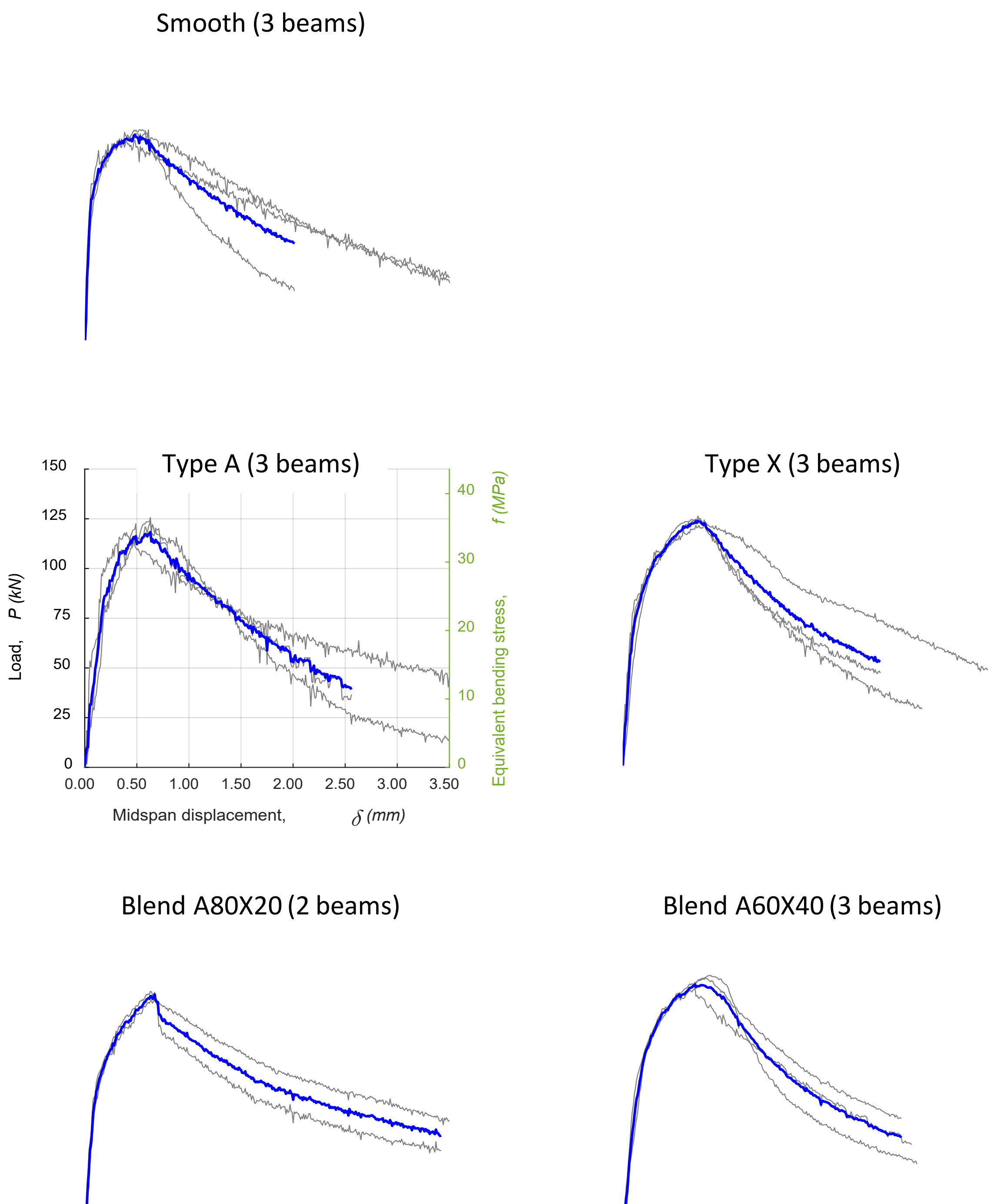


**FIGURE 29: Flexural tests (steel fiber $V_f = 2\%$)**

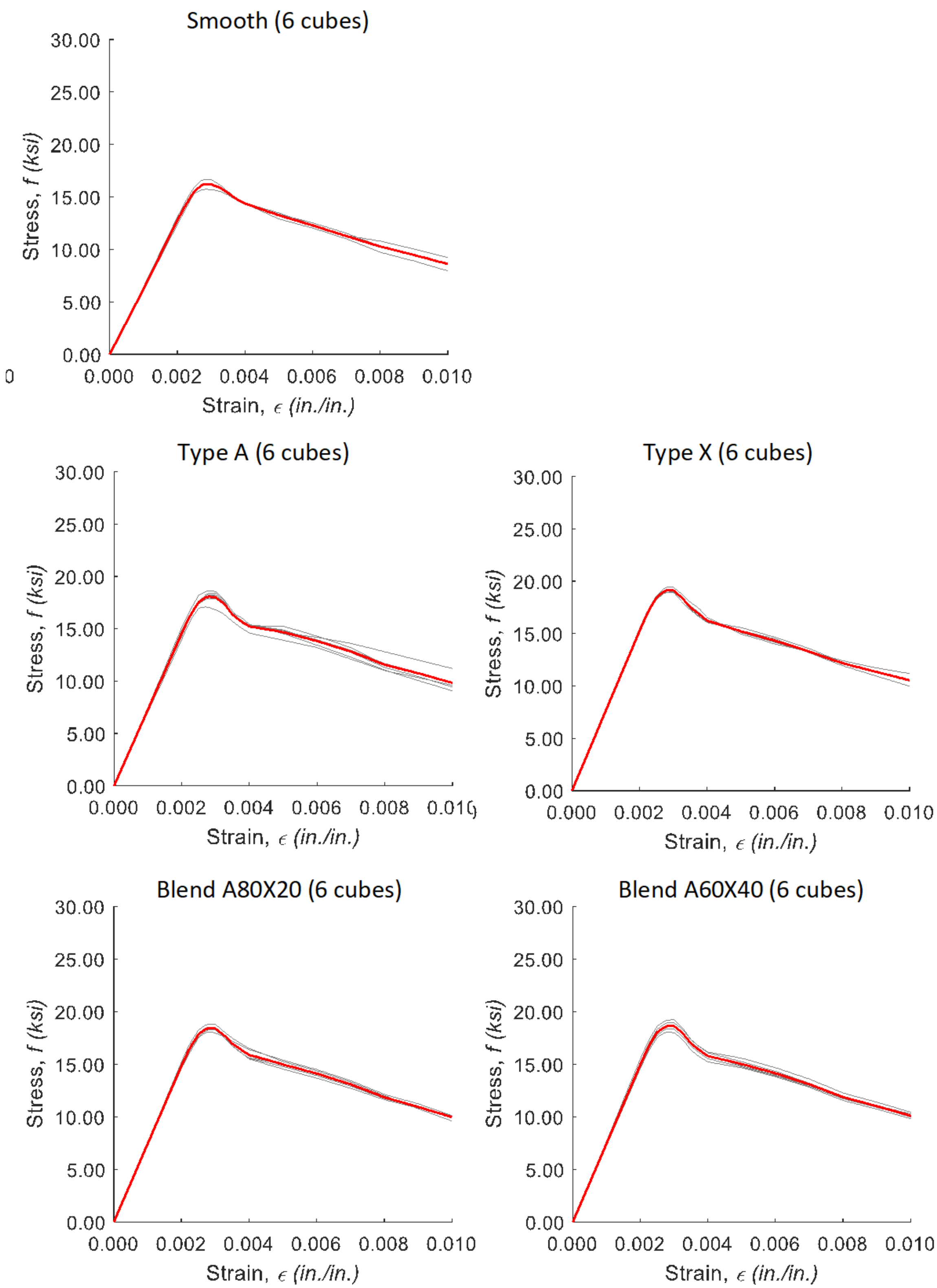


**FIGURE 30: Compression tests (steel fiber $V_f$ = 1%)**

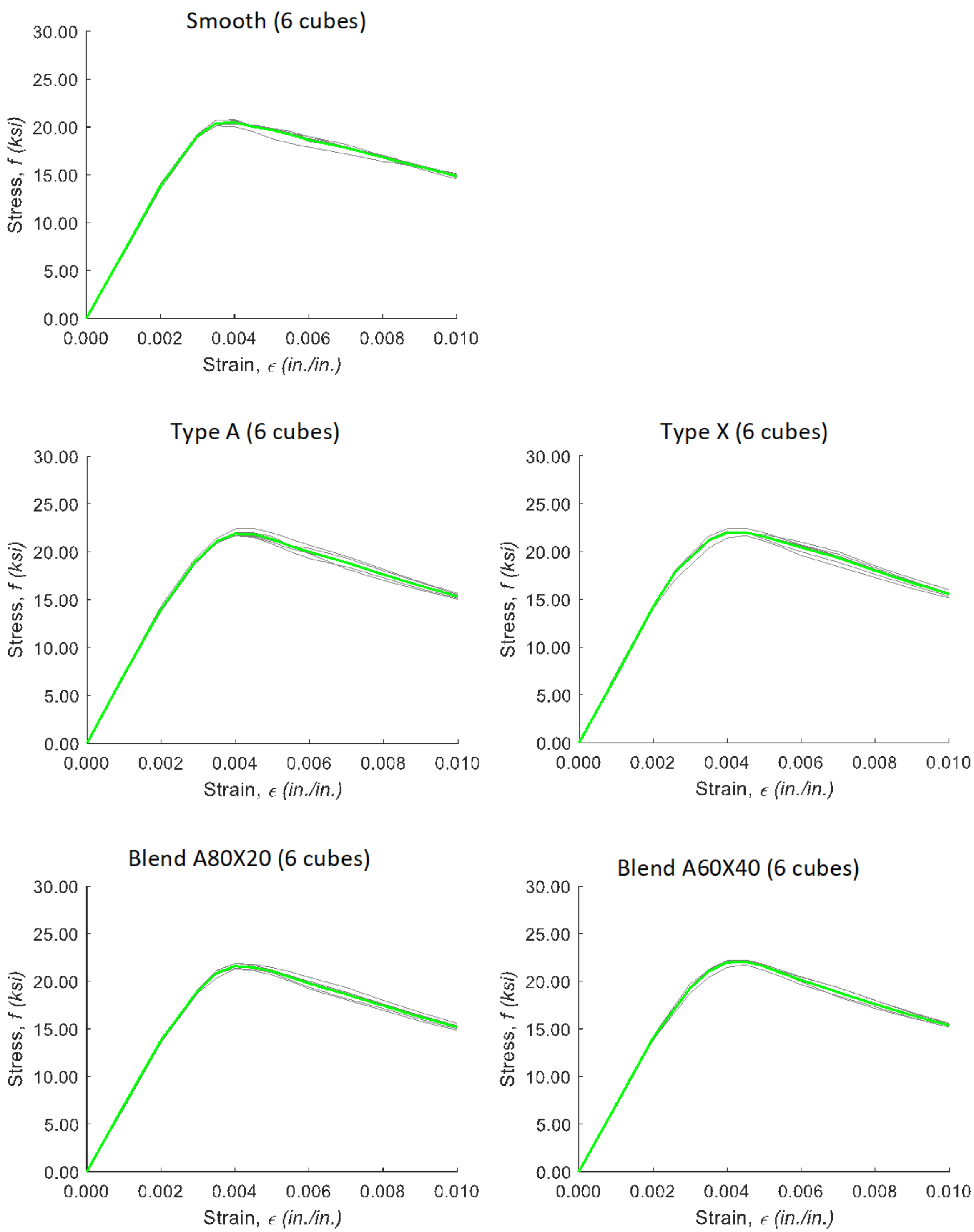


**FIGURE 31: Compression tests (steel fiber $V_f$ = 1.5%)**

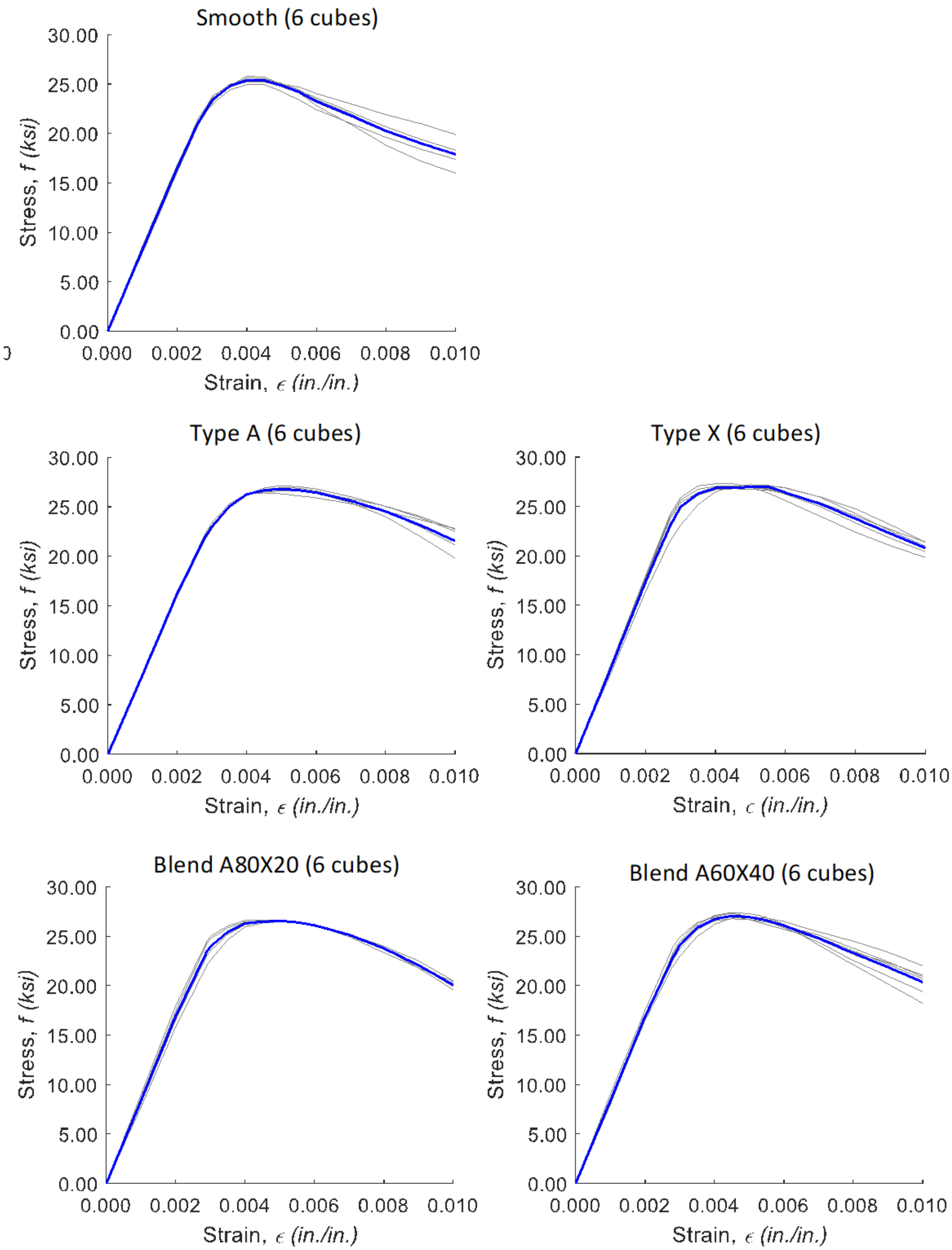


**FIGURE 32: Compression tests (steel fiber $V_f = 2\%$)**

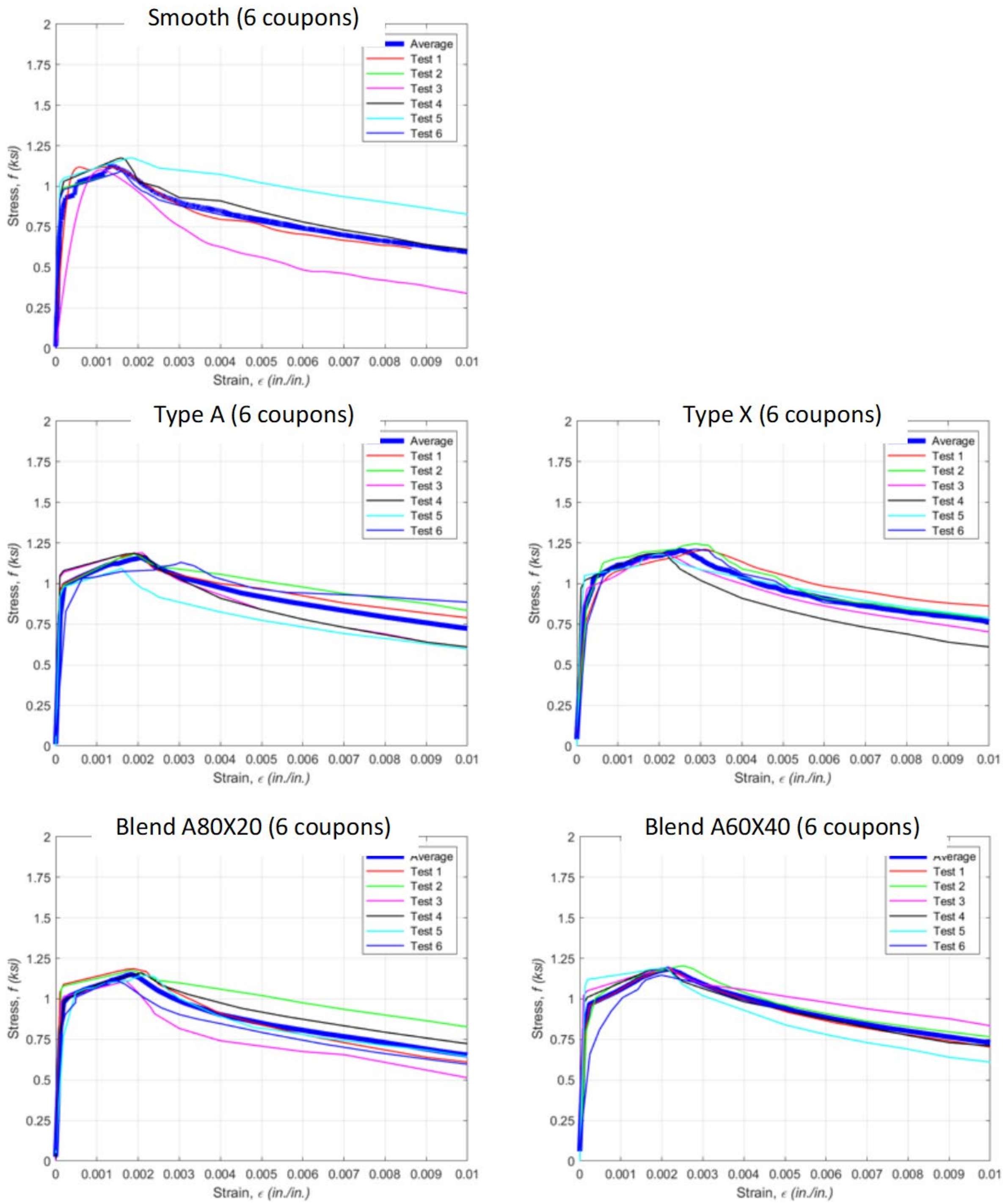


**FIGURE 33: Tensile coupon tests (steel fiber $V_f = 1\%$)**

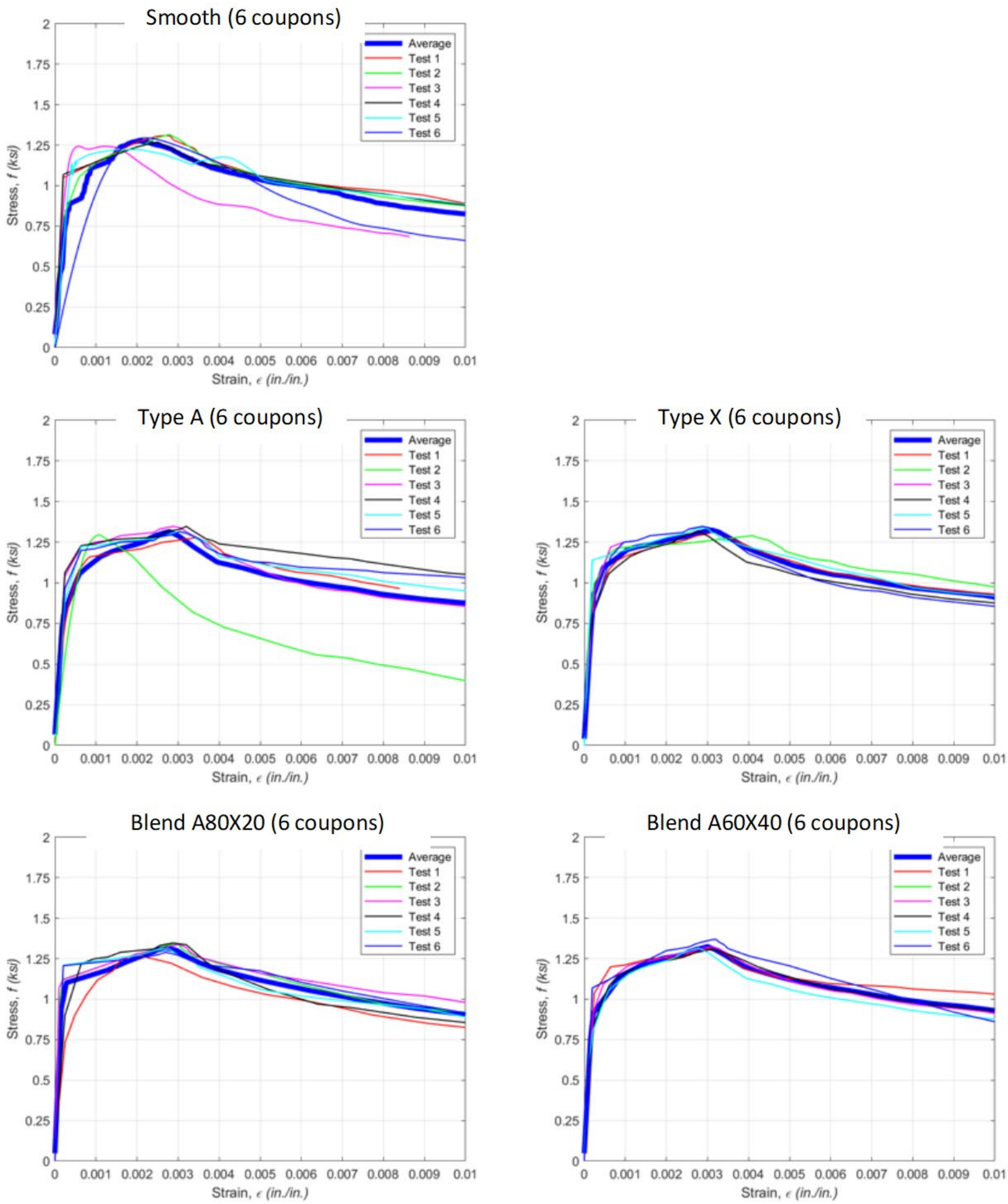


**FIGURE 34: Tensile coupon tests (steel fiber $V_f$ = 1.5%)**

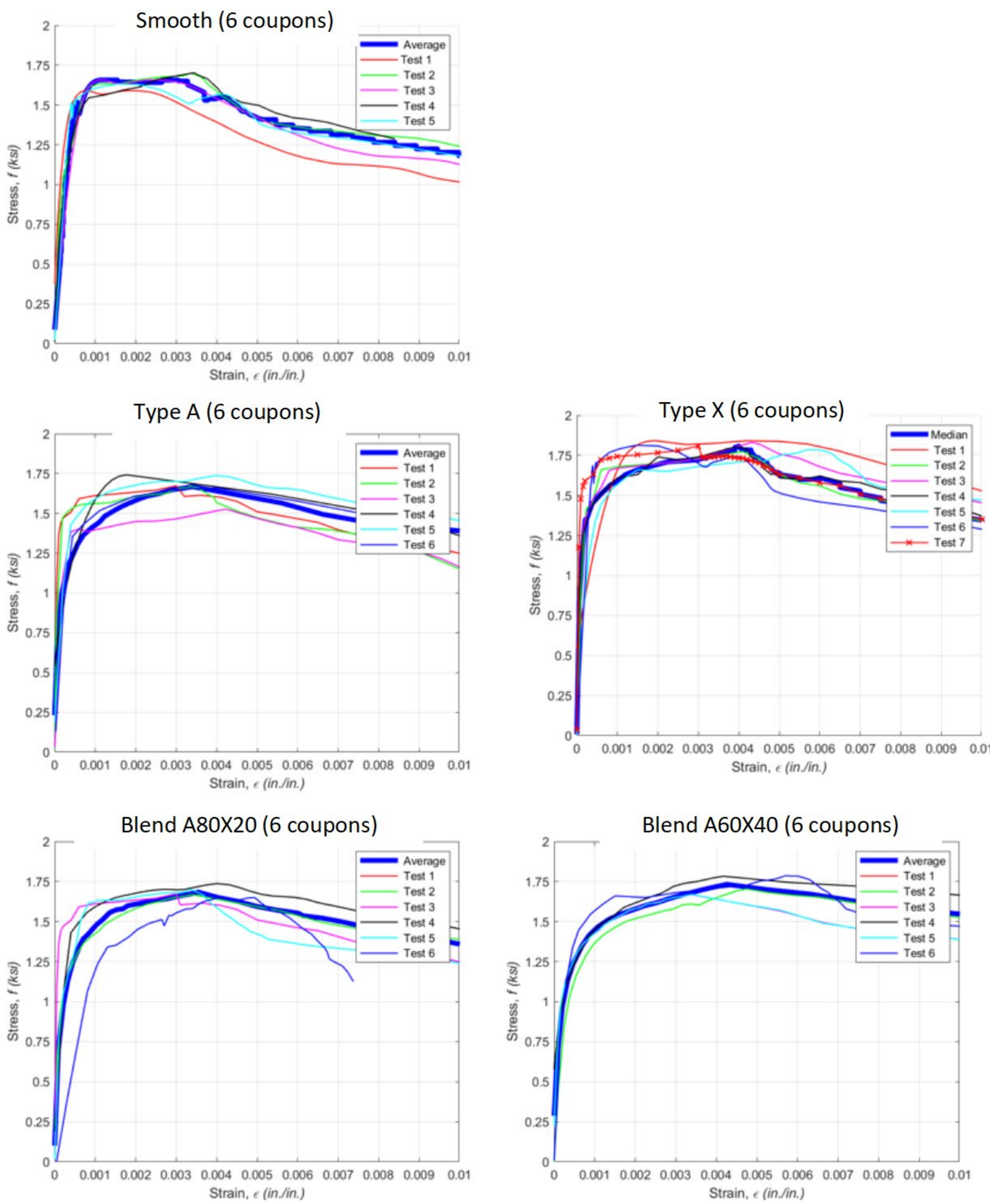


**FIGURE 35: Tensile coupon tests (steel fiber $V_f$ = 2%)**

## APPENDIX II: RESEARCH RESULTS

Sidebar Info
Program Steering Committee: NCHRP IDEA Program Committee
Month and Year: October 2022
Title: High Bond Steel Fibers for Ultra High-Performance Concrete (UHPC)
Project Number: NCHRP 20-30/IDEA 235
Start Date: 10/31/2021
Completion Date: 12/31/2022
Product Category: Steel Fibers
Principal Investigator: Sherif El-Tawil
Name, Title: CEO, HiPer Fiber, LLC
E-Mail: eltawil@hiperfibersolutions.com

TITLE: High Bond Steel Fibers for UHPC
SUBHEAD:
This project developed a novel type of steel fiber to more efficiently reinforce UHPC and demonstrated its use in a recently built bridge.

WHAT WAS THE NEED?
Previous research has shown that the type of steel fiber most used in UHPC utilizes only 32% of each fiber's tensile capacity suggesting that the fibers are highly underutilized. This is ironic given that the steel fibers represent 72% of the raw material cost. HiPer Fiber, LLC, has invented a new type of steel fiber (named HiPer fiber, patent pending) that has the potential to triple the fibers' utilization rate, thus dramatically raising its efficiency and opening the door to substantial benefits.

WHAT WAS OUR GOAL?
Develop a new type of fiber that is more efficient at reinforcing ultra high performance concrete and demonstrate its use in an actual bridge.

WHAT DID WE DO?
The initial research effort focused on identifying the optimal fiber design and developing a viable technique to manufacture the fibers in commercial volume. An experimental testing program was then conducted to assess the effectiveness of the new fiber. The experiments showed that the surface-modified fibers had a 130% increase in pullout resistance compared to non-modified fibers (i.e. more than double the capacity of the non-modified fibers). When used to reinforce UHPC at the traditional dosage of 2% by volume, the new fibers resulted in a 62% increase in strain at peak stress (the so-called localization strain) compared to specimens with non-modified fibers, i.e. it increased UHPC's ductility by close to two-thirds. When used at a reduced dosage of 1% by volume, i.e. half the regular dosage, the new fibers resulted in a performance that was on par with non-modified fibers at full 2% dosage.

Once the new fiber technology was perfected, a demonstration effort was undertaken to showcase its capabilities. The demonstration effort focused on the Bricker Road bridge over the Quackenbush Drain, which is owned by the St. Clair County Road Commission (a research partner). The bridge had a deteriorated reinforced concrete slab deck that was due for replacement. A set of replacement UHPC deck panels reinforced with the new fibers were designed and constructed. The UHPC panels were only about one third of the weight of the original reinforced concrete panels. Data collected during the project demonstrated that mixing the new fibers into the UHPC went smoothly and that the resulting field mix's spread was comparable to lab-mixed UHPC. Tension coupons and compression cube samples collected during the field trial showed that the field-mixed UHPC achieved mechanical properties that were just below the properties of lab-mixed UHPC, but still well above the design values.

The demonstration bridge is the first bridge in the US in which the entire deck was made with open-recipe UHPC mixed in a traditional ready-mix truck. It decisively demonstrates the potential for using common concrete equipment for mixing UHPC. This paves the way for broader utilization of UHPC across the United State. The results of this project also indicate that by using the new steel fibers, it is feasible to reduce the dosage of steel fibers to 1% to 1.5% by volume from the traditional 2% by volume. Since steel fibers are the most expensive component of UHPC (accounting for up to 72% of the raw material cost), reducing fiber dosage this way will profoundly reduce the upfront cost of UHPC and hence broaden its appeal and usage.