Draft Technical Memorandum

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Task 3: Development and Critical Evaluation of Tensile Test Methods and Establishment of Tensile Strength Classes

Submitted to
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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation or the U.S. Department of Transportation.

Prepared in cooperation with the State of Florida Department of Transportation and the U.S. Department of Transportation.

Approximate Conversions to SI Units (from FHWA)

Symbol	When You Know	Multiply By	To Find	Symbol
Length				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
Area				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
Volume				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
Mass				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
Temperature (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
Illumination				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
Force and Pressure or Stress				
lbf	pound-force	4.45	newtons	N
lbf/in^2	pound-force per square inch	6.89	kilopascals	kPa

Activities Performed During Period project start to 012/15/2020

TASK 3 – Development and Critical Evaluation of Tensile Test Methods and Establishment of Tensile Strength Classes

Status: This task is complete

CHAPTER 1. UHPC TENSILE STRENGTH CLASSES AND QUALITY CONTROL TESTING

1.1. Introduction

Ultra-high-performance concrete has become increasingly popular in the United States in the past decade. Many states and private companies are now looking to develop their own non-proprietary UHPC mixtures to save money in large-scale projects. With an increase in the number of possible suppliers and mix designs for UHPC comes the added difficulty of determining mix approval and quality control requirements. This is especially true when it comes to testing tensile strength and behavior of UHPC. Because traditional concrete without fiber-reinforcement does not have tensile strength after cracking, there are no widely used quality control tensile tests for concrete that capture the entire failure behavior. Flexure tests can give an indirect measure of tensile behavior but require displacement sensors and data logging systems that are not available in most concrete testing laboratories. Direct tension testing of concrete often requires uncommon specimen shapes and expensive gripping equipment in addition to a sophisticated data logging system.

This study compared three different tension testing methods: the direct tension test developed by the Federal Highway Administration (FHWA), the flexural test described in ASTM C1609, and a simplified double-punch test based off of the Spanish norm UNE 83515 [1]–[3]. Two different types of steel fiber were each tested at 5 different doses to see how well the simpler test methods would reflect the results of the direct tension test. Recommendations were then made on how the simpler test methods could be used for quality control testing.

1.2. Materials and Methods

All specimens were made using the same concrete mix design and changing only the type and amount of fiber used. The fiber types are described in Table 1-1. The mix proportions are shown in Table 1-2. A plot of particle size distribution for the dry materials is shown in Figure 1-1.

Table 1-1: Fiber Properties

Geometry	**Material**	**Coating**	**Length Inches (mm)**	**Diameter Inches (mm)**
straight	steel	brass	0.50 (13)	0.008 (0.20)
twisted	steel	none	0.50 (13)	0.02 (0.50)

Table 1-2: Mixture Proportions

Material	**Weight (lb/yd^3)**
Sand	1585
1L Cement	1597
Slag	309
Silica Fume	155
Water	240
High-range water reducing admixture	30.9
Water reducing and workability retaining admixture	30.9
Surface enhancing admixture	5.2

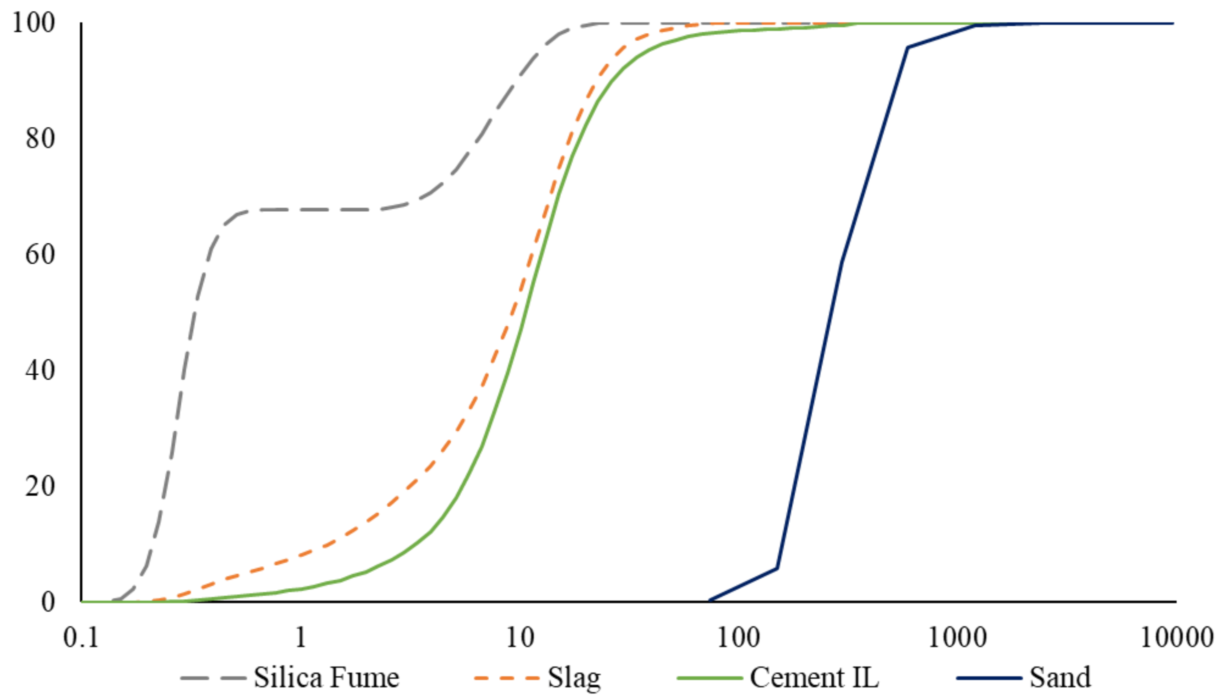

Figure 1-1: Particle size distribution of aggregate and cementitious materials used

Each of the two types of fibers (referred to as straight and twisted fibers for the remainder of this report) were tested at five different dosages. The target volume percentages for fibers were 1.0%, 1.5%, 2.0%, 2.5%, and 3.0%. However, actual fiber percentages were each 7% lower than the targets. For example, the mix targeting a 1.0% of fibers by volume actually had only 0.93%, and the mix targeting 3.0% actually had 2.79%. For simplicity, the original target percentages will be referred to in this report.

The mixes were made using a vertical shaft high-speed mixer with a 1 ft^3 capacity. Dry materials were added to the mixer as it mixed with a slow speed of less than 10 rpm to homogenize the materials. After homogenization, the water was added slowly, followed by the admixtures. Mixing speed was increased to a medium speed of approximately 30 rpm for roughly 3 minutes, followed by fast mixing at 50 rpm for the remainder of the mixing time. The concrete was mixed for at least 30 minutes before fibers were added, followed by 5 minutes of mixing to disperse the fibers. Because of the limited mixer capacity, two separate batches were made for each mix. The flexure specimens were made from one batch, and the double-punch and tension specimens were made from the other. Compression cylinders were made from each batch as a quality control measure and to see if fiber percentage and type impacted compressive strength.

Six specimens were made for direct tension testing for each fiber type and dosage. The direct tension test method from the FHWA was followed, with the addition of added C-clamps at the top and bottom of the specimen at the tapered portion of the aluminum plates [1]. This addition was found to reduce the number of specimens that cracked outside of the region where expansion was measured. Specimens that failed outside of this measured region were excluded from the analysis because an accurate stress vs. strain graph could not be produced. Fabricating six specimens from each mixture design ensured that there were at least 3 valid tests for each mixture design. A schematic of the specimen and test set up in the grips is shown in Figure 1-2. Specimens were made from steel molds 2 × 2 × 17 inches. From the direct tension test, the following values were calculated: the maximum stress, the stress at a strain of 0.005 in./in., and the toughness (area under the curve) up until 0.005 in./in. of strain.

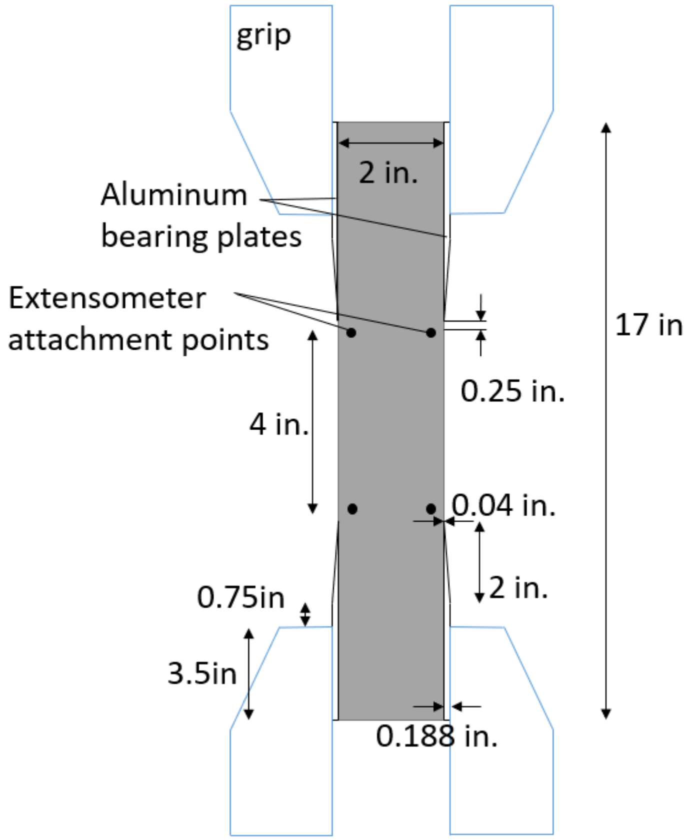

Figure 1-2: Direct tension testing set-up

Four 4 in. × 4 in. × 14 in. flexural specimens were made for each mixture design, ensuring that at least 3 of each were successful. **Error! Reference source not found.** shows a schematic of the test set-up. The value "a" in Figure 1-3 is equal to 4 inches for this test. The test was performed according to ATM C1609. The values calculated and used for analysis were the maximum bending stress, also referred to as the "modulus of rupture," the stress at a deflection l/600, the stress at a deflection of l/150, and the toughness (area under the curve) up until the deflection of l/150 was reached.

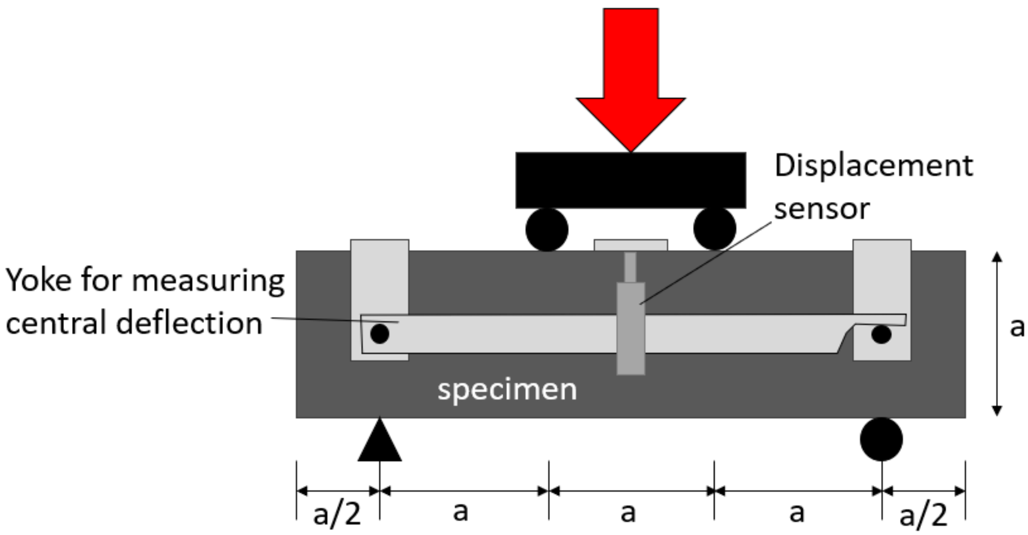

Figure 1-3: Flexure testing set-up

The double punch test used for this study was a modified version of UNE 83515, commonly known as the "Barcelona Tests" [3]. Three 6 in. × 6 in. cylindrical double-punch specimens were made from plastic molds for each mix. This test was simplified so it could be performed in a standard compression testing machine with simple mechanical displacement gauges. A schematic of the simplified test method is shown in Figure 1-4. While the original test method uses a circumferential extensometer to measure displacement, this method used a dial gauge to measure vertical displacement of the specimen. Circumferential and vertical displacement-measuring techniques have been shown to be related to each other in the double-punch test [4], [5]. In order to further simplify the testing, a dial gauge was used as the displacement-measuring device, and readings of load vs. displacement were taken manually by the technician at set displacement intervals. For the first 0.10 inches of displacement, readings were taken every 0.01 in. From 0.10 in. – 0.30 in., load was recorded every 0.02 in. Testing of concrete specimens made from the same batch of concrete showed that taking discreet readings at increments less than or equal to 0.025 in. did not alter the overall toughness results by more than 2 percent. A load rate was selected to give a displacement rate similar to that used in UNE 83515. After the specimen neared failure, no adjustments were made to the machine load rate dial for the remainder of the test. Specimens were loaded at a load rate between 200-600 lb/sec during the linear portion of the load vs. displacement curve. Testing on specimens made from the same batch of concrete showed that a load rate between 200 and 800 lb/sec produced no statistically significant change in toughness or peak strength results for the double-punch test. From the double punch data collected, the loads were converted to stresses using Equation 1-1.

$$f'_t = \frac{4 * Q}{9 * \pi * a * H} \qquad \text{Equation 1-1}$$

Where f'_t is the tensile stress, Q is the applied load, a is the diameter of the steel punches, and H is the height of the cylinder [3]. The maximum stress was reported, along with the stress at a displacement of 0.14 in. and the toughness calculated as the area under the stress vs. displacement curve.

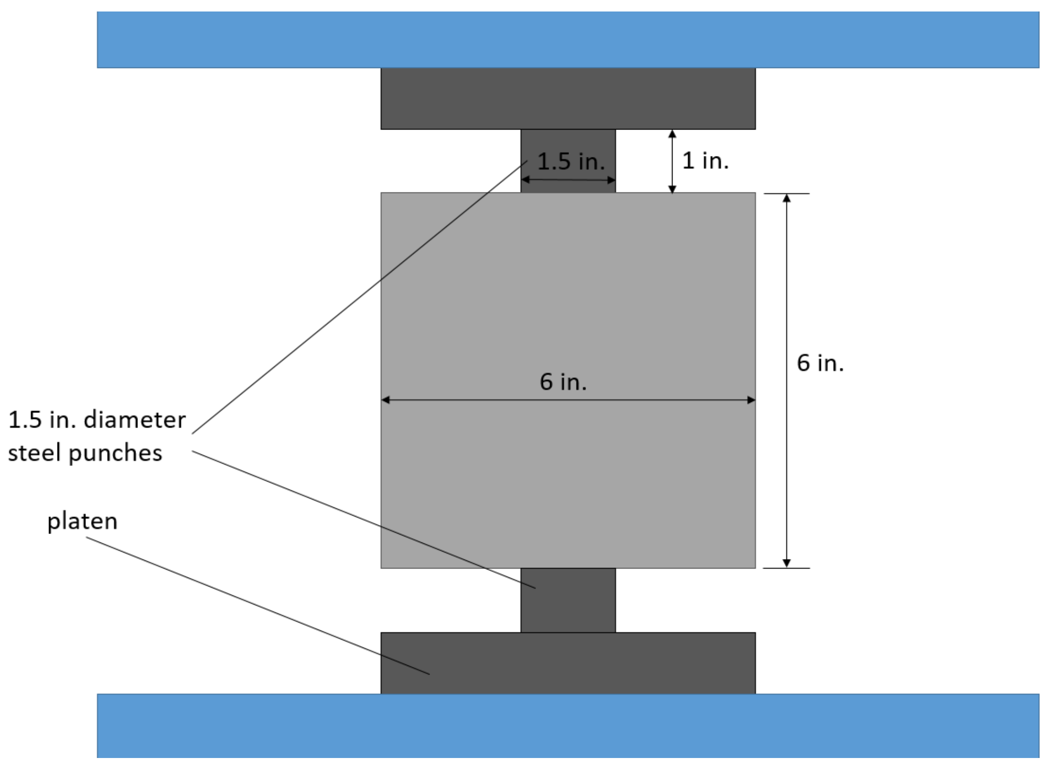

Figure 1-4: Simplified double-punch test set-up

1.3. Results

Because of the large amount of data collected for this study, graphs of every successful trial of every test are presented in Appendix A. Trials where the specimen cracked in a location unacceptable for data analysis were not plotted and were not considered in the calculation of average values. Graphs showing average values include error bars representing the standard deviation of the replicates for the particular mix.

Figure 1-5 through Figure 1-7 shows the average maximum stress values calculated from direct tension testing, flexure, and double punch for each mix, respectively. Of the three types of values calculated from each test (maximum stress, stress at specified point, toughness), the maximum values were the least affected by both fiber type and fiber dose. This is because even specimens with low amounts of fiber could have a relatively high strength in the cementitious matrix alone. Many specimens with low doses of fibers had very high cracking strengths in flexure or tension, followed by a sharp decrease in load right after cracking. As fiber dosage increased and specimen behavior became strain-hardening, trends relating fiber percentage and maximum stress were more apparent. This can be especially noticed in the straight fiber specimens with 2-3% fibers. Values from these mixes were higher than values from the other 7 mixture designs, for which maximum stress values ranged from 750-1000 psi. It can reasonably be assumed that concrete with a compressive strength of 17,000 psi could have a tensile strength in this range, even without any fiber reinforcement. Equation 1-2 is often used as an estimate of when concrete will crack in tension.

$$f_t' = 7.5\sqrt{f_c'} \qquad \text{Equation 1-2}$$

Where f'_t is the tensile strength and f'_c is the specified compressive strength [6]. Concrete with a specified compressive strength of 17,000 psi would then have an estimated tensile strength of 978 psi. In strain hardening specimens, the maximum stress of the concrete exceeded the stress exhibited during the first crack because the fiber matrix was stronger than the uncracked cementitious matrix. Specimens made with 2-3% straight fibers exhibited strain-hardening behavior, while the specimens made with twisted fibers did not. In direct tension testing, initial cracking stresses were highly variable because they depended on specimen alignment. A specimen that was slightly misaligned would have a lower initial cracking stress than a perfectly aligned specimen. If the specimen were strain hardening, it could account for these mis-alignments after cracking by bending and re-distributing load. However, the more brittle specimens could not regain strength after cracking, causing very high standard deviations to be calculated for these specimens.

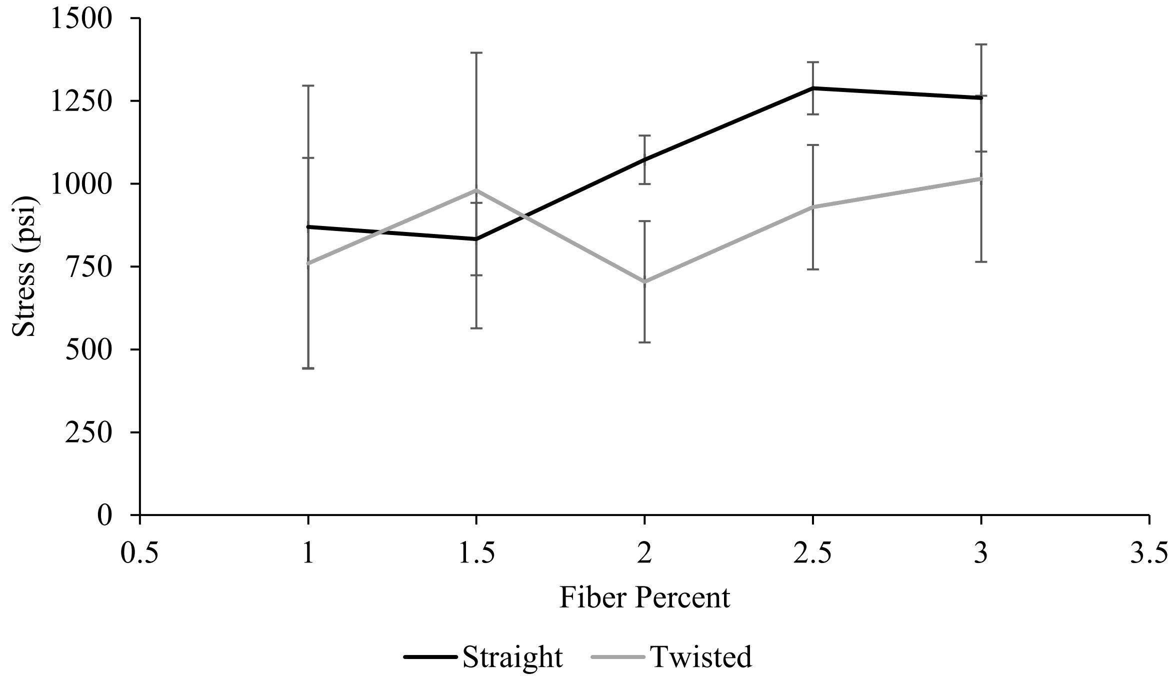

Figure 1-5: Average maximum stresses from direct tension testing

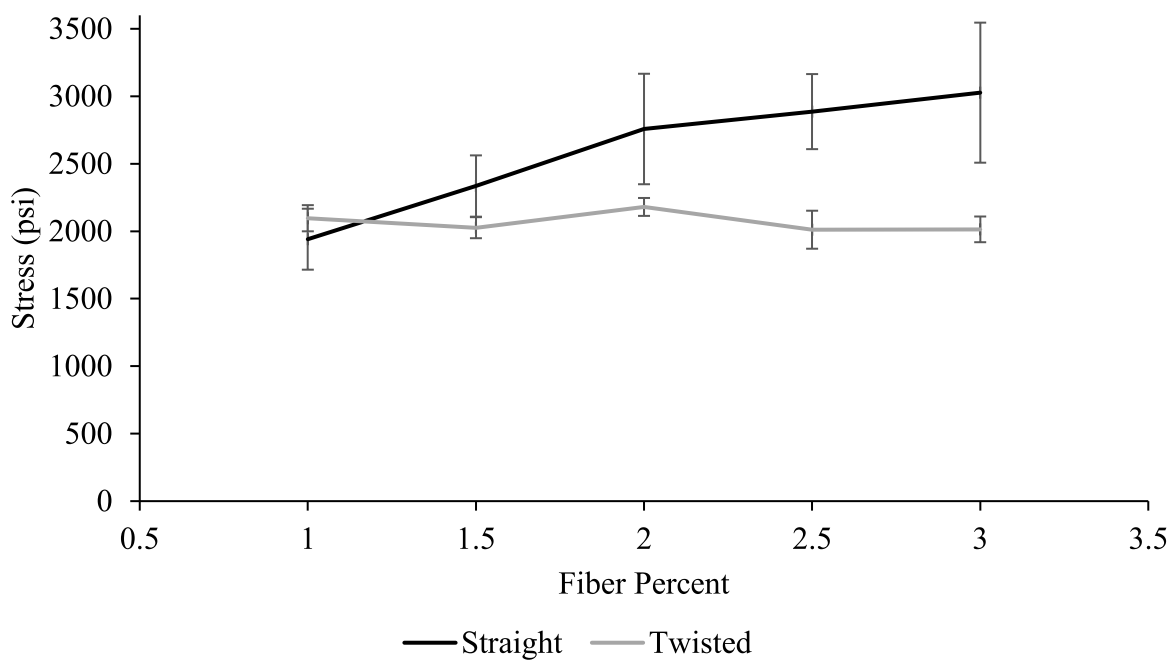

Figure 1-6: Average maximum bending stresses (moduli of rupture) from flexure testing

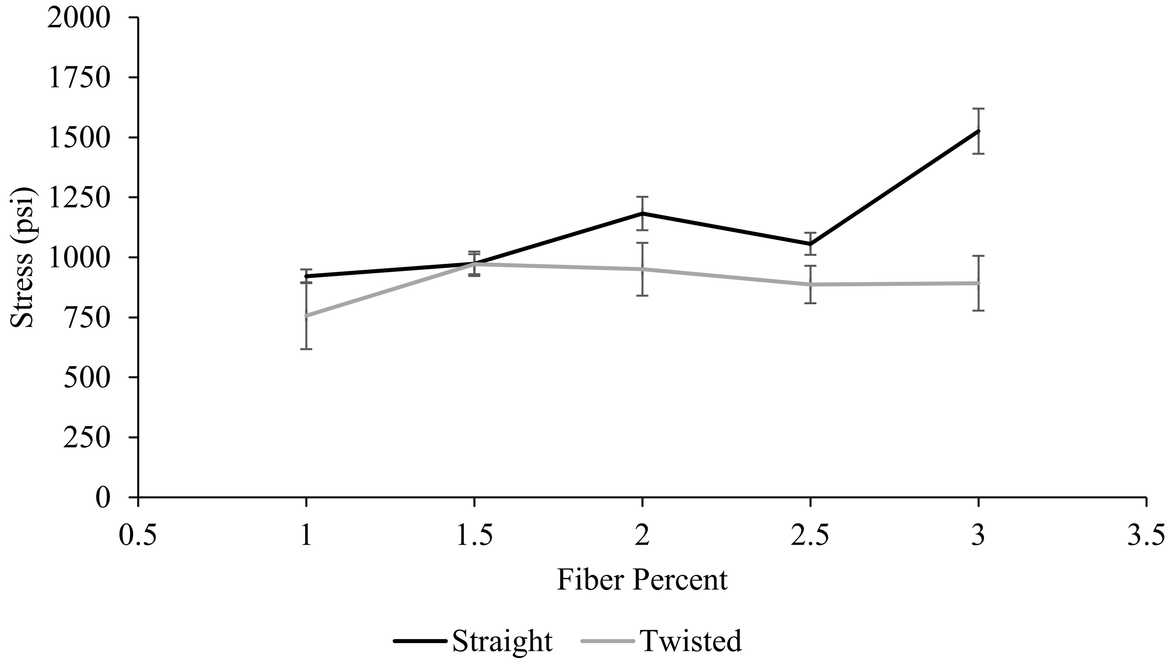

Figure 1-7: Average maximum tensile stress from double-punch testing

The results from flexure and double-punch testing showed similar results for the maximum stress values. No relation was found between maximum stress and fiber percentage for the twisted fiber mixes, and a slight increase for straight fiber mixes. For all three tests, the R^2 value for maximum stress was below 0.1 for Helix mixes. The R^2 value was between 0.5 and 0.7 for straight fiber mixes. These R^2 values were calculated using all of the trial values for each test, not only the averages. From the error bars plotted in the average graphs, it can be seen that the flexure and double-punch tests had lower standard deviations in maximum stress when compared to the direct tension test. This was especially true for the twisted fiber mixes and the less-ductile straight fiber mixes. This makes sense as the direct tension test produced a main failure plane of only 4 in.^{2} while the flexure and double-punch tests had failure planes of 16 in.^{2} and 36 in.^{2}, respectively. A failure over a larger area would be less affected by defects in the specimen, such as air voids or pockets of preferentially-oriented fibers.

Some specifications used in the United States for UHPC require only a maximum stress value to be reported for either flexure or direct tension testing [7], [8]. This includes Florida, which only requires a strength of 1,200 psi to be reached in the ASTM 1609 flexural test [7]. While

Florida's section 927 only applies to proprietary concrete mixes and specimens tested for this research were made from non-proprietary UHPC, every mix tested in this study would meet the tensile requirements for Florida's current specification. This could be misleading because it does not consider ductility, and while the specimens made with twisted fibers reached a stress of higher than 1,200 psi, the mixes with lower fiber contents were not able to maintain that load after cracking. For this reason, it is recommended that if only one tensile parameter is included in an approval specification, it should not be a maximum value for any test. For example, Colorado only requires that the maximum value be greater than the first peak value of the ASTM C1609 flexural test [9]. This is similar to Canadian and Swiss requirements that use a minimum ratio of maximum stress to first peak stress in conjunction with a minimum first peak strength to approve UHPC mixes [10], [11]. While this may be difficult to determine in specimens that do not have an obvious first crack, it does a better job of taking the entire tensile behavior into account than simply using the maximum strength value.

Some states that do not have any tensile requirements at all choose instead to require a minimum amount of fiber to be included in a mix [12], [13]. While this may be a useful requirement in conjunction with other tensile requirements or with a list of specific approved fibers, the results from this research show that fiber content by itself does not predict behavior. A fiber's aspect ratio, thickness, and geometry may influence its effectiveness in transferring load to the cementitious matrix.

For this research, the additional parameters studied to help represent behavior were toughness and stress at a specified displacement. Figure 1-8 through Figure 1-10 show how the average toughness changed with respect to fiber type and amount. While this change is still only slightly evident in the twisted fiber mixes, it is clear that the straight fiber mixes gained toughness as fiber percentage increased. One large discrepancy can be seen in Figure 1-10, where the specimens made with 2.5% straight fibers had a low double-punch toughness compared to what would be expected in the trend. The cause for this is unknown, as the double-punch specimens were made in the same mix as the direct tensile specimens, and no abnormal behavior was seen in the toughness of the 2.5% straight fiber direct tension tests. Peak stress was also low for the 2.5% straight fiber double-punch specimens, as shown in Figure 1-7.

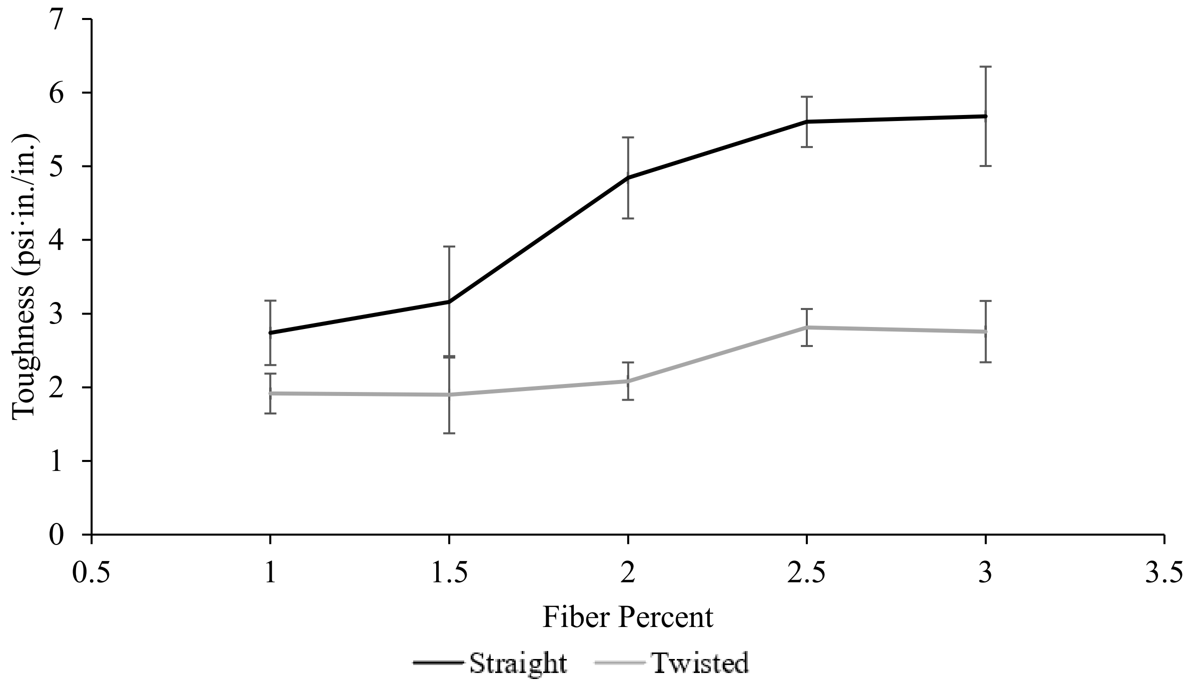

Figure 1-8: Average toughness from direct tensile testing

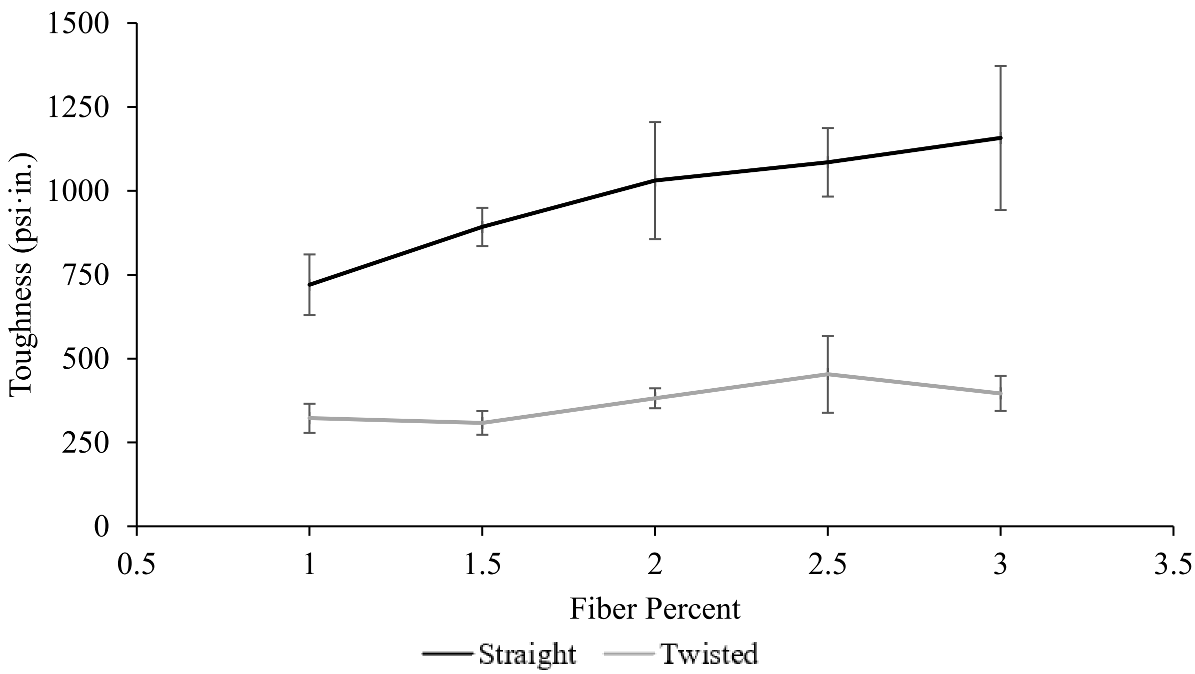

Figure 1-9: Average toughness from ASTM C1609 flexural testing

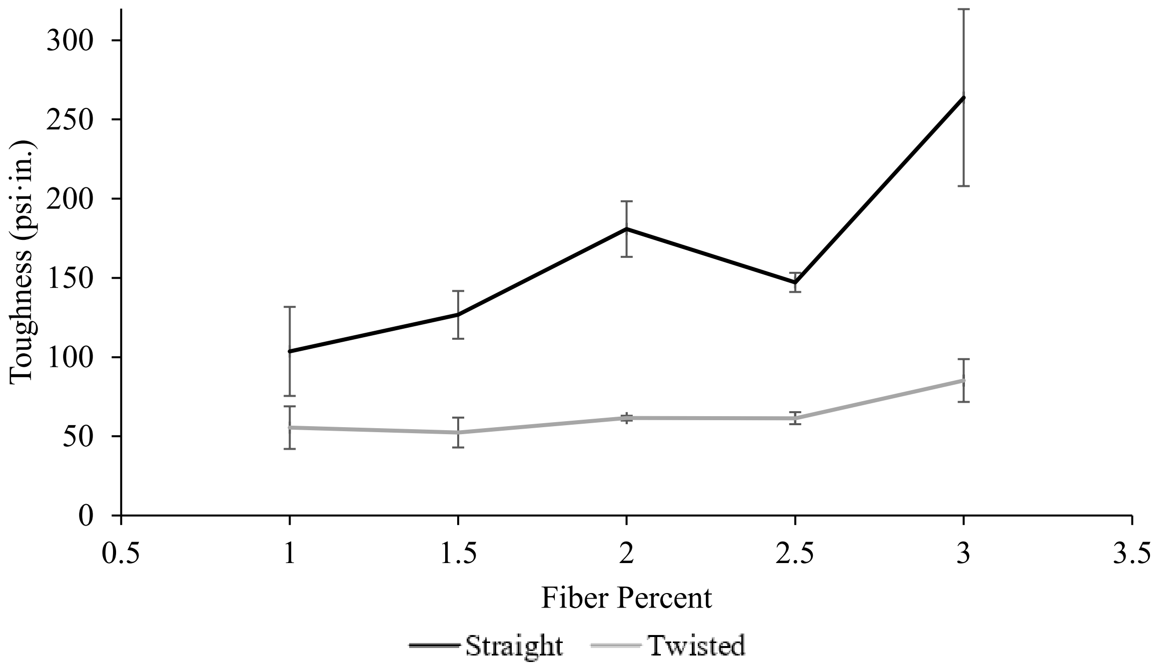

Figure 1-10: Average toughness from double-punch testing

The final parameter studied for each test method was the stress at a specified strain. ASTM C1609 requires that the stress be reported at specified deflections of l/600 and l/150, so both of these values were investigated [2]. For a span of 12 inches, these deflections corresponded to 0.20 in. and 0.80 in., respectively. For the tension tests, a specified strain of 0.005 in./in. was chosen [6]. A structural engineer may be interested in the tensile strength of the concrete at this point. Some of the 1% twisted fiber specimens did not reach this strain, so their values were not used for the calculation of the average. For the double-punch test, a displacement of 0.14 inches was chosen. This value was chosen to be large enough so that it would occur after the peak stress for each mix.

The average values for stresses at specified strains are presented in Figure 1-11 through Figure 1-14. An upward trend was clearly visible for the straight fiber specimens as fiber content increases, while the twisted fiber specimens showed less of a change. The 2.5% straight fiber double-punch specimens had surprisingly low stress values. It is thought that this could be a result of material non-homogeneity during placement. Selecting a specific deflection or strain at which to compare stresses can be a useful tool to measure specimen ductility. However, it is important that the location be determined so that the stress value is taken from the same portion of every specimen. For example, a very ductile double-punch specimen may not experience peak stress until after 0.10 inch of displacement; therefore, the displacement selected must take this into account so that the comparison isn't made between a pre-peak value of one specimen and a post-peak value of another. This issue was present when finding the flexural stress values at a deflection of l/600, as this value was measuring a value before the maximum stress for most of the straight fiber specimens but a post-peak value for all of the twisted fiber specimens. In addition, for the low-fiber content twisted fiber flexure specimens, the initial crack often caused a large displacement of over 0.02 in. to occur almost instantaneously, meaning there were no data points taken at a deflection of 0.02 inc. In these cases, a weighted average was taken of the points before and after a 0.02 in. deflection was reached to determine the stress at 0.02 in. However, this was not necessarily equivalent to the flexural stress that the specimen would hold at 0.02 inches; it was likely an over-estimate. The stress readings at a deflection of l/150 (0.80 inches for this study), all occured after the peak stress had been reached, giving a more comparable number between fiber types. When comparing the readings at 0.8 in. to those at 0.2 in. of deflection, it can be seen that the twisted fiber specimens exhibited a large decrease in strength, typically a decrease of 65-80 percent. The straight fiber specimens lost about 15% of their strength for the 2%-3% specimens. The 1% and 1.5% specimens actually had higher stresses at a 0.8 in. deflection than at a 0.2 in. deflection. Similar trends are found when comparing the stress at 0.8 in. of deflection to the maximum stress, or modulus of rupture. Twisted fiber specimens lost 75-90% of their maximum stress, while straight fiber specimens lost only 10-25 percent. A metric like this could be used to confirm specimen ductility, but it would penalize specimens that had a higher maximum stress, all else being equal. A single value at a specified displacement may be preferred, especially in direct tensile testing where stresses at known strains may be desired for design calculations. One downside of directly transferring tensile behavior from the direct tensile test to a design scenario is the gauge length over which strain is measured. The 4 in. region may have multiple cracks form in it, but typically only one or two of these cracks are responsible for the majority of the strain measured. The strain is really an average strain over the arbitrarily determined 4 in. distance. While this test has been widely-accepted in the UHPC research community, a researcher using a different direct tension test may see different results simply because of the length over which the strain is measured. If a 2 inch region is used and the localized crack forms within it, the strain readings would be roughly twice as large as those calculated from a 4 inch region, which could make it appear to be more ductile than it actually is.

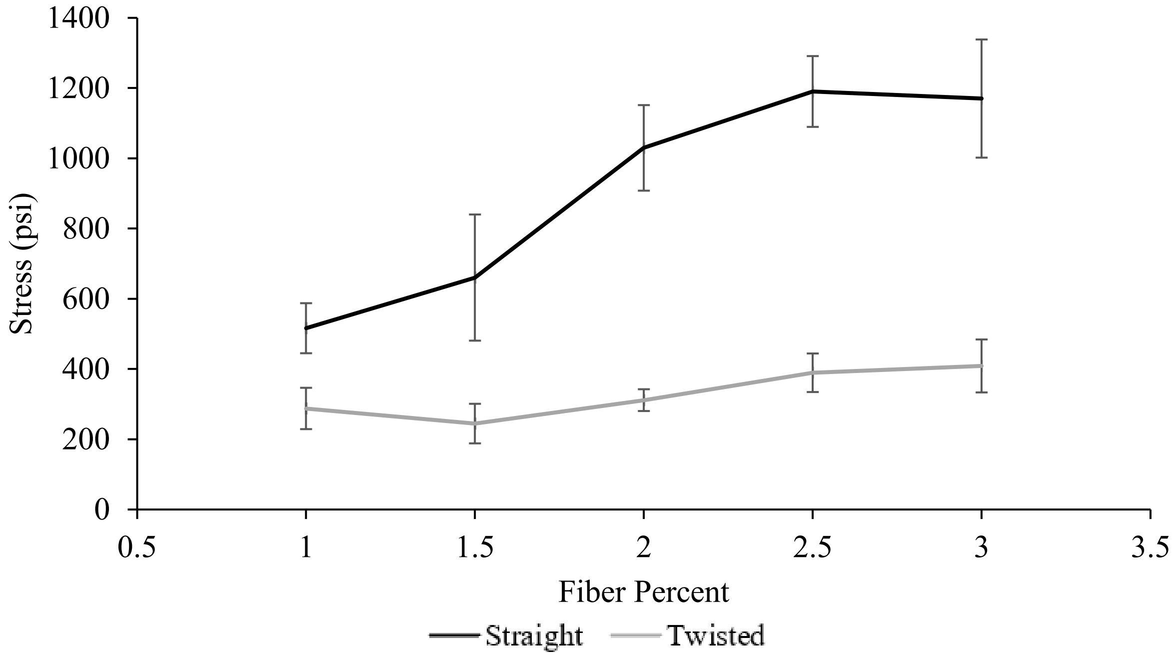

Figure 1-11: Average direct tensile stress at 0.005 in./in. strain

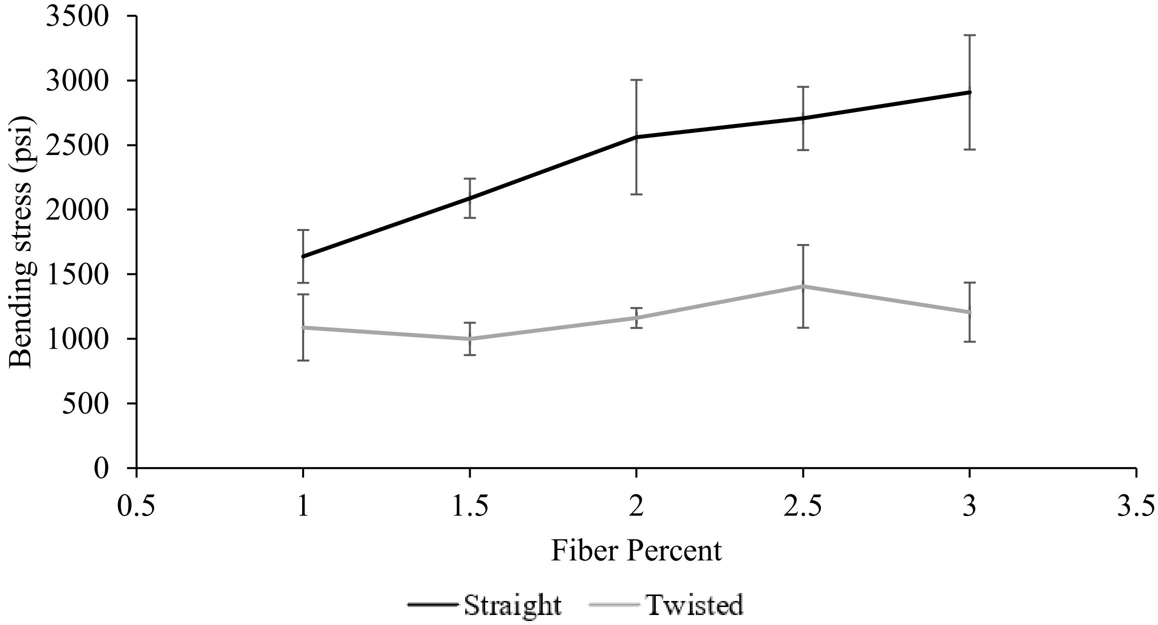

Figure 1-12: Average flexural stress at a deflection of l/600

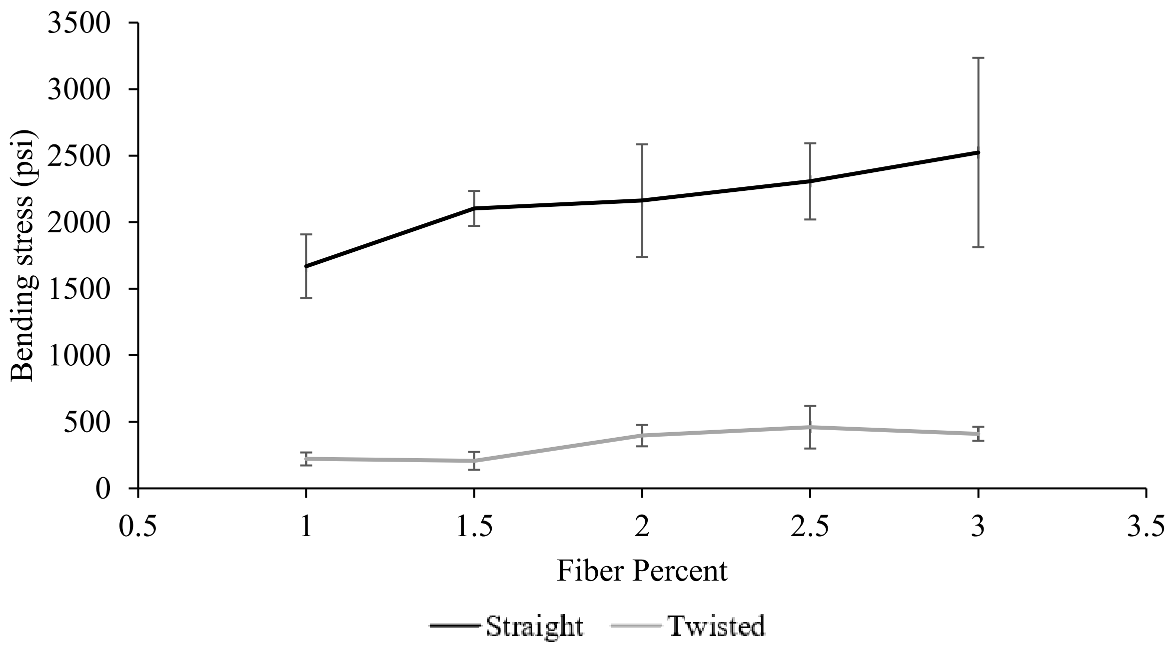

Figure 1-13: Average flexural stress at a deflection of l/150

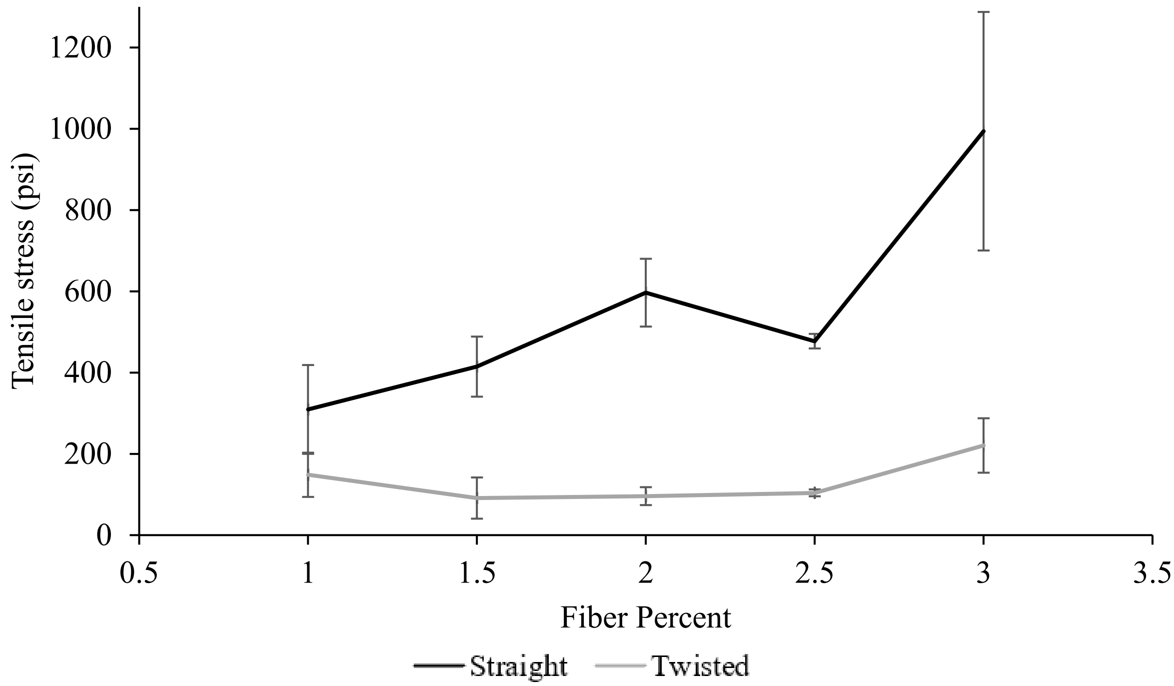

Figure 1-14: Average double-punch tensile stress at a vertical displacement of 0.14 inches

A purpose of this study was to determine whether the results of simpler methods (ASTM C1609 and modified double-punch) would reliably reflect the results of the more-complicated direct tensile method so that it could be used as a quality control test in Figure 1-15 and Figure 1-16. The results were compared by plotting direct tension values on the independent (x) axis and the simplified methods on the dependent (y) axis. An equation and R^2 value were calculated for each comparison. As expected, there was not a high correlation between the maximum stresses of each test, as the maximum stresses within each test method was highly variable. When an intercept of 0 was set, it was found that the regression line slope relating the maximum stress for direct tension and double-punch specimens was very close to 1. This would allow for the use of the modified double punch test in quality control tests to measure UHPC peak tensile strength. When the intercept was set for the flexure test, however, the best fit equation had a multiplier of over 2. This means that on average, a mix with an average maximum stress in direct tension of 1,000 psi would exhibit a maximum stress in flexure of roughly 2,370 psi. Therefore, it is important that the current Florida requirements for UHPC in flexure be increased, preferably to 2,300 psi or higher, or require the use of inverse calculations to obtain the direct tension stress-strain relationship from ASTM C1609 results.

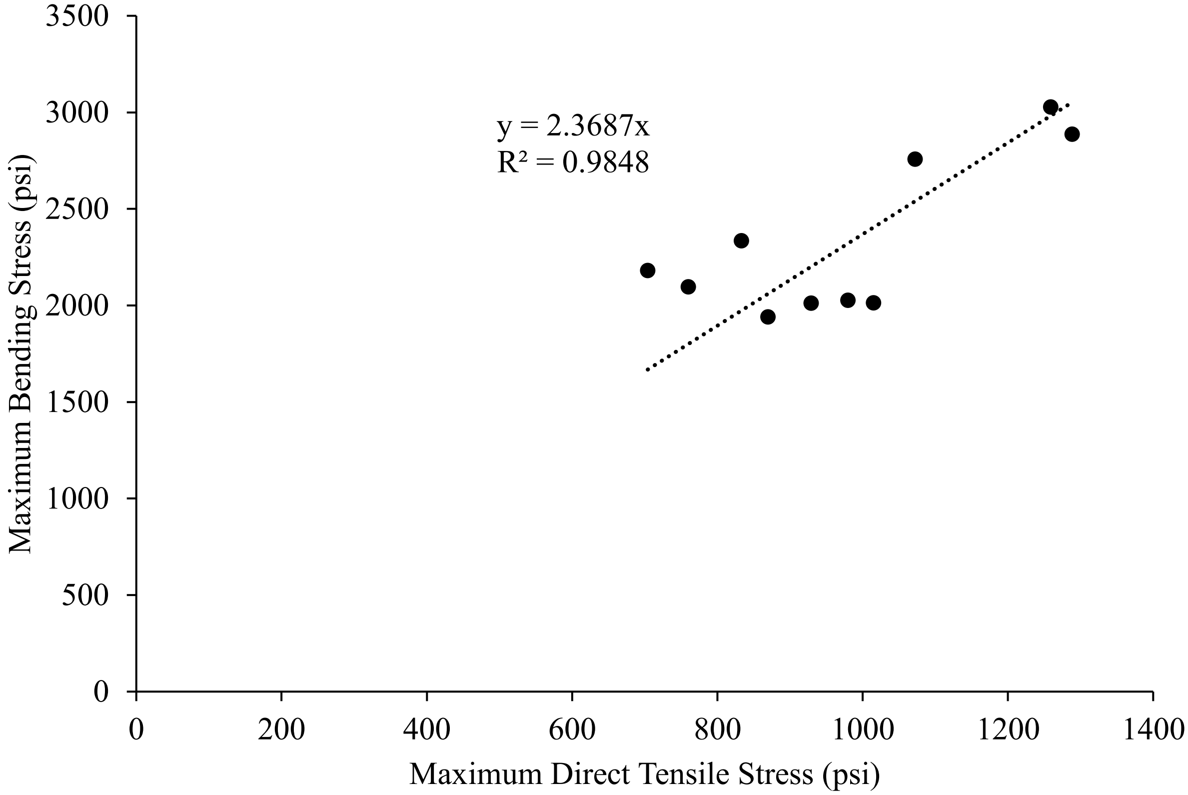

Figure 1-15: Relationship between maximum bending stress in ASTM C1609 and maximum direct tensile stress for specimens tested

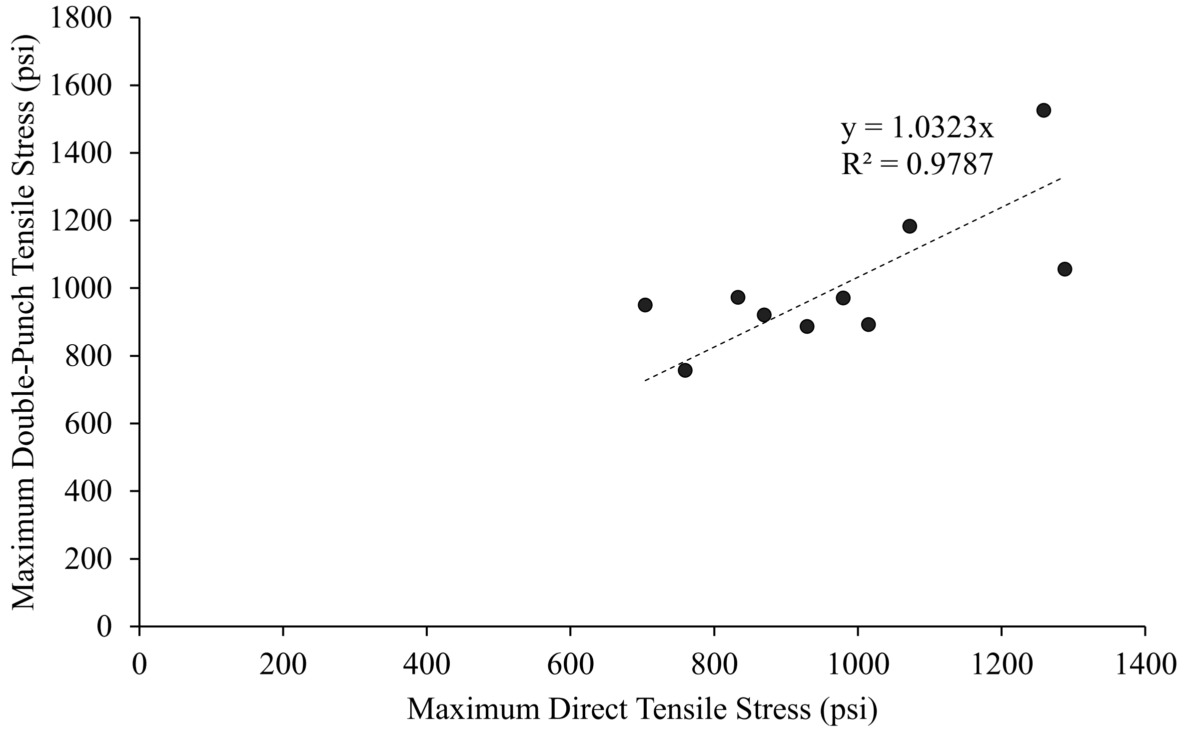

Figure 1-16: Relationship between maximum double-punch tensile stress and maximum direct tensile stress for specimens tested

Toughness values showed a much higher correlation between tests than the maximum values did, as shown in Figure 1-17 and Figure 1-18. Both the flexure and double-punch tests showed an R^2 value of higher than 0.8, indicating a good correlation. Toughness values for both flexure and double-punch testing showed a larger gap between the twisted fiber and straight fiber mixes than the direct tensile toughness did. In direct tension, the 1% straight fiber specimens had lower toughness than the 2.5% and 3% twisted fiber specimens. However, it showed higher toughness in the double-punch test than all twisted fiber specimens, and the difference in the flexure test was even more pronounced. Looking at the actual direct tension curves for these mixes, it can be seen that at the strain of 0.005 the straight fiber specimens with 1% fiber content had higher strength than the equivalent specimens made with twisted fibers, which also seemed to lose strength with displacement at a faster rate. This suggests that if the toughness calculation for the direct tensile test was changed to be over a range longer than 0.005, the 1% straight fiber specimens would have shown a higher toughness than those made with twisted fibers. While tensile behavior preference will change based on the application of a concrete, the behavior of the 1% straight fiber specimens will usually be preferable to that made with 3% twisted fiber, as the stress retained after cracking is more reliable. For a strain hardening mix, neither of these options would be approved; however, this comparison shows the importance of making a toughness determination over a longer portion of the stress vs. strain curve. It is suggested that if a toughness value were to be used for determining tensile class, it be calculated until a strain of 0.01 in./in.

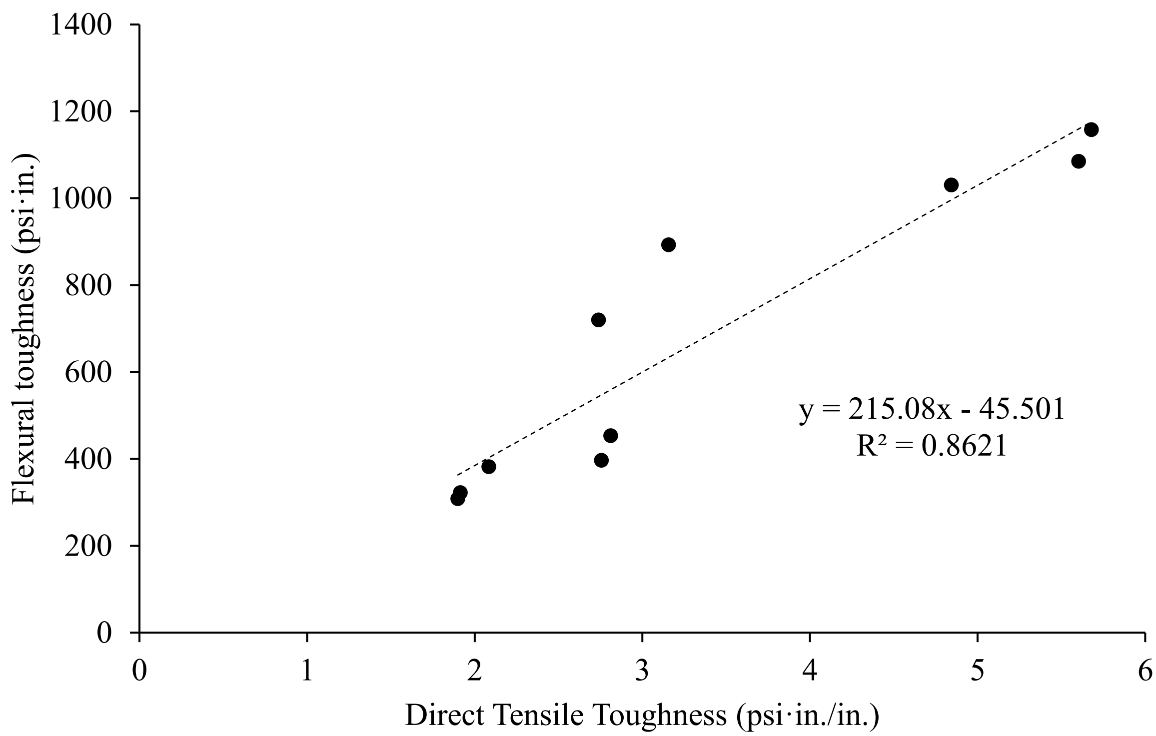

Figure 1-17: Relationship between flexural toughness and direct tensile toughness

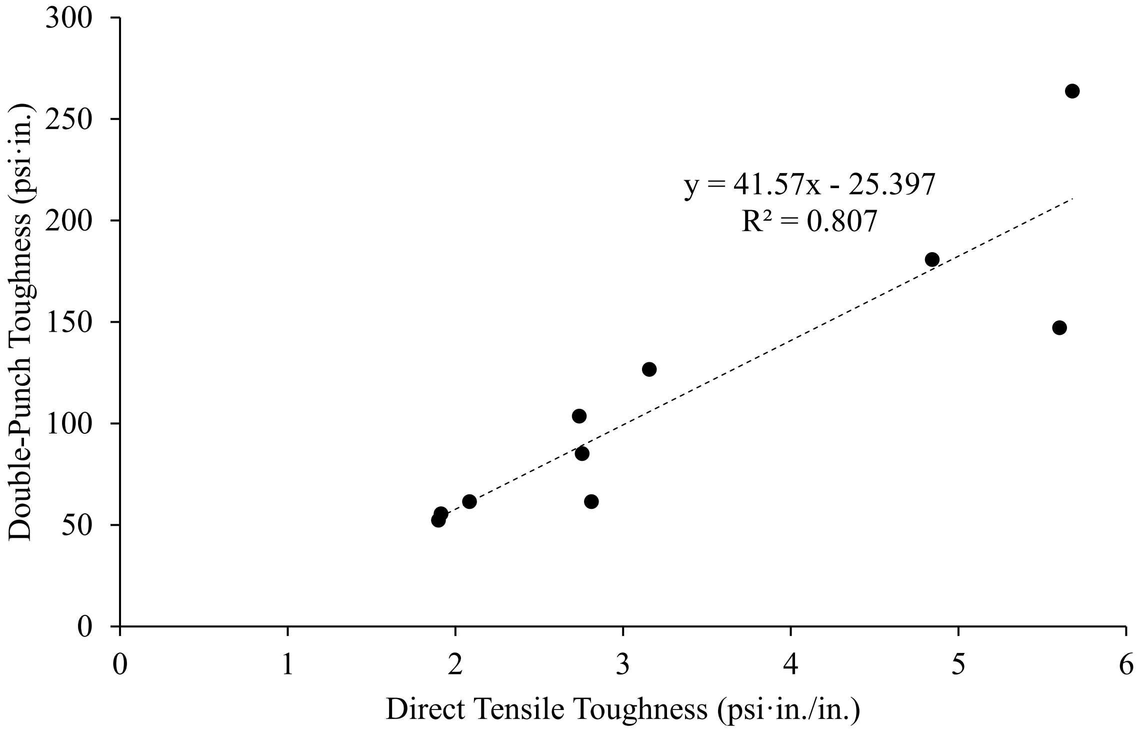

Figure 1-18: Relationship between flexural toughness and direct tensile toughness

Comparison of the stresses at specified displacements of the flexural or double punch specimens with that of the direct tension specimens had R^2 values near or above 0.8 as shown in Figure 1-19 through Figure 1-21, which were similar to the toughness correlations. Once again, the flexure test had higher correlation than the double punch test, although it is likely that a replicate of the 2.5% straight fiber double punch mix would improve its values. The flexure stress at a deflection of l/600 had an extremely high correlation with the tensile stress at 0.005 strain, with an R^2 value higher than 0.97. When the flexure stress at l/150 was compared, the correlation decreased. This appears to be due to the high stress values achieved by the 1% and 1.5% straight fiber specimens at this deflection. As mentioned earlier, they averaged a higher stress at the larger deflection than at the smaller one. These correlations show that either the flexure or double punch test could be reliably used for quality control testing in place of direct tension testing.

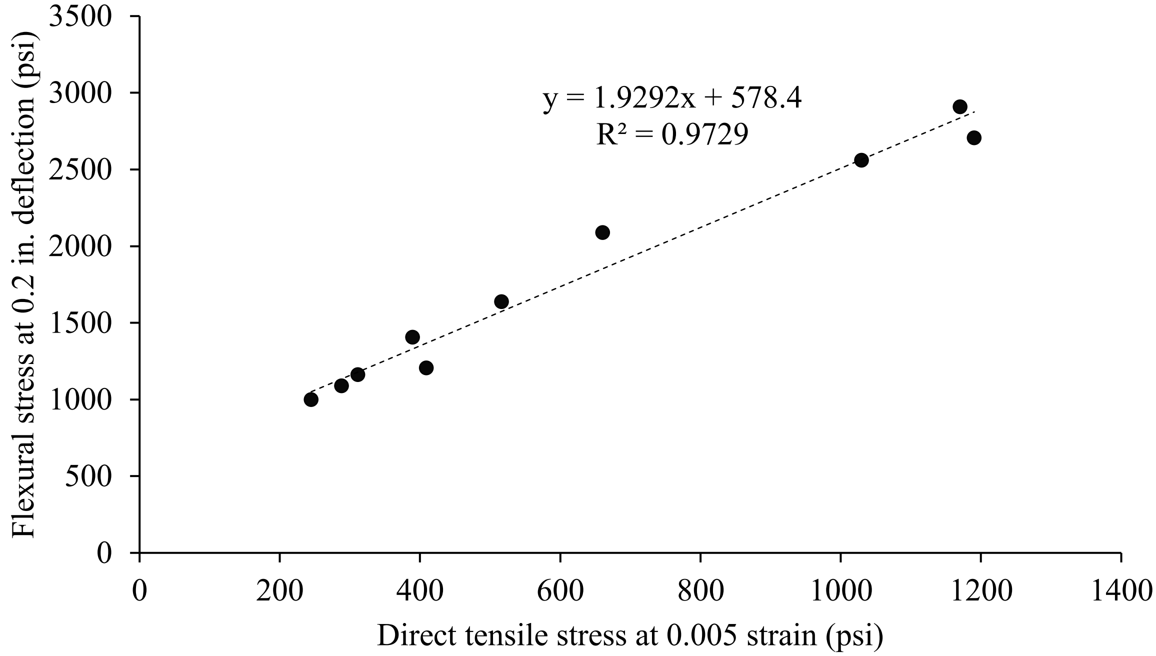

Figure 1-19: Flexural stress at l/600 (0.2 in.) vs. direct tensile stress at 0.005 strain

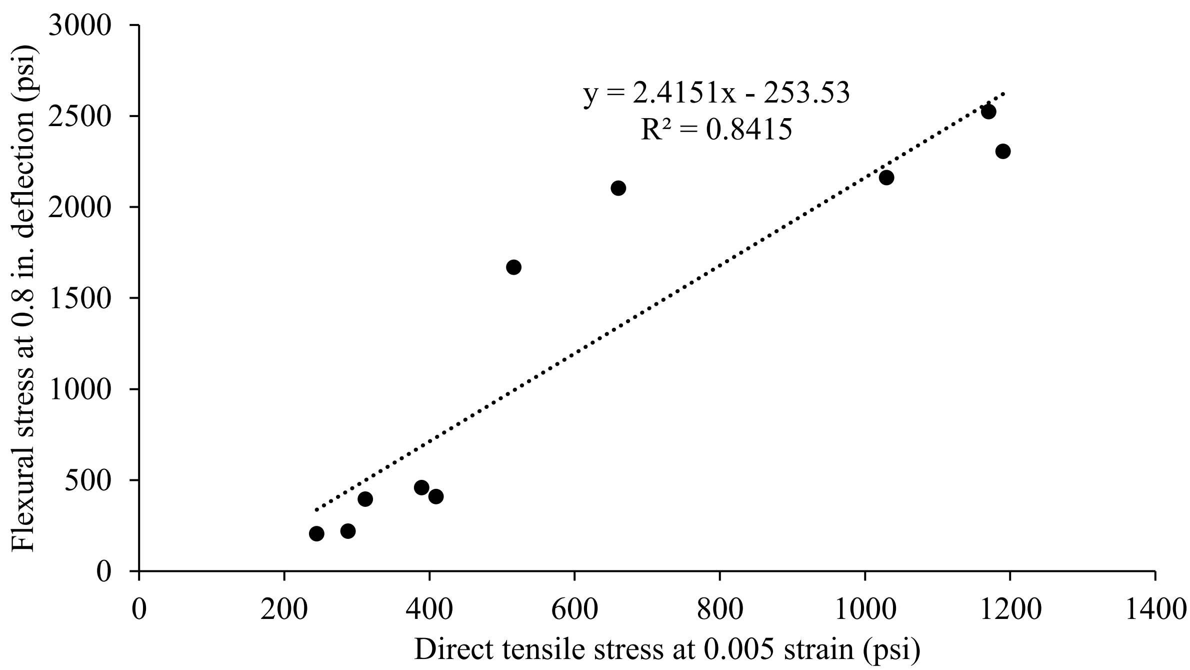

Figure 1-20: Flexural stress at l/150 (0.8 in.) vs. direct tensile stress at 0.005 strain

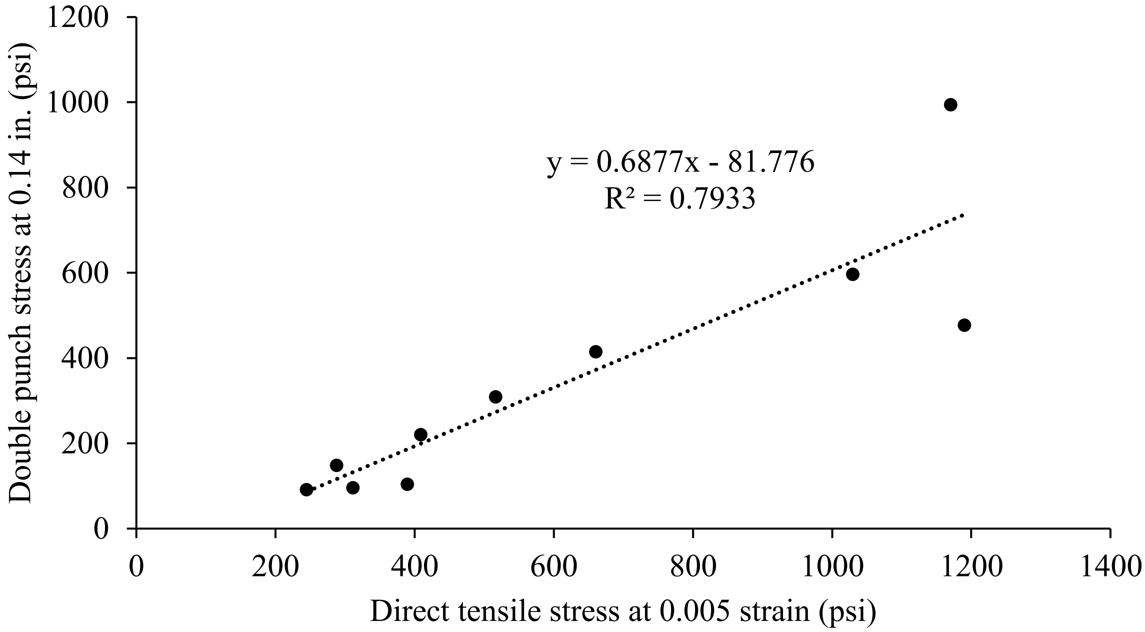

Figure 1-21: Double-punch stress at 0.14 in. vs. direct tensile stress at 0.005 strain

Tensile strength classes were developed to be used in Florida for non-proprietary UHPCs. The preferred test method to use when designating a UHPC mix into its appropriate strength category is the direct tensile test. While researchers have proposed inverse analysis techniques to characterize UHPC tensile behavior [14]–[16], they rely on assumptions of the stress vs. strain behavior and/or the curvature of the cracked specimen [17]. Many specification agencies use a ratio of maximum stress to peak stress to approve a mix or determine a mixture tensile class [10], [11].The downfalls of this method are that it can require a subjective determination of the first cracking stress and that a higher initial cracking stress can lead to the rejection of an otherwise ductile mix. For these reasons, it is recommended that Florida Department of Transportation (FDOT) use stress at a specified displacement to determine a mixture's appropriate tensile class. Mixtures with at least 2% of the straight steel fibers tested tend to be strain hardening, while mixes with 1 or 1.5% appear strain softening or elasto-plastic. All of the mixes with twisted fibers exhibited a steady decline in tensile strength as strain increased. Specifying a stress at a particular strain ensures that mixes with high maximum tensile stresses but low ductility would not be approved as a strain-hardening UHPC. A value of 900 psi at 0.005 strain is approximately equal to the average value for the 2% straight fiber specimens tested minus one standard deviation. If this were used as a criterion for a strain-hardening tensile strength class, the 2%, 2.5%, and 3% straight fiber mixes would be approved, while the 7 others would not. Because some specimens are still increasing in strength at 0.005 strain and may not yet have reached their maximum strength, (such as the1.5% straight fiber trial 1 and 2% straight fiber trial 4), it should be acceptable to use the best strength value reached after a strain of 0.005 in.

1.4. Summary and Recommendations

It is recommended that direct tension tests be used as a quality approval test because it does the best job of showing overall stress vs. strain behavior. Some mixes that are not strain hardening, such as the mixtures made with 1% and 1.5% straight fiber, will appear strain hardening in a flexure test, although a direct tension test will show that they are clearly not. In addition, the direct tension test will give results that are most easily correlated to design, as the stress values in the flexure test are not direct tensile stresses, but bending stresses, which are usually over twice as large, as seen in Figure 1-15. The suggested minimum requirements for tensile strength classes based on this research are shown in Table 1-3. This table uses two criteria to determine strength class: the maximum stress the specimen reaches and the stress the specimen has at 0.005 strain. A third category is present for the enhanced strain hardening class, to ensure materials characterized in this class maintain a high strength even at 0.01 strain.

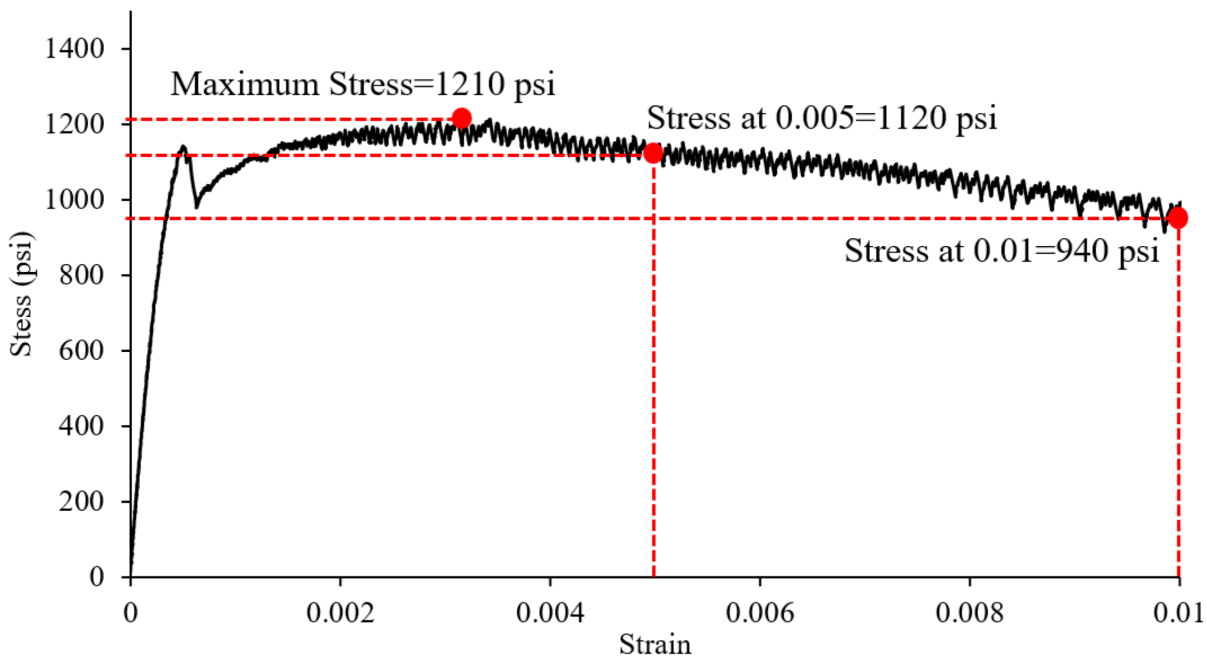

Figure 1-22 shows a schematic of the results from a direct tension test and which points would be used for mix qualification. The direct tension results shown in the figure would qualify as enhanced ductility UHPC because all three points are above the required values. A mix design being tested for qualification would need to have multiple specimens tested in this way, with the average in each category exceeding the tensile class requirement. It is suggested that at least 6 specimens be used in testing for qualification of a mix, with no more than 3 excluded for cracking outside of the area used to measure specimen strain. Using Table *1-3*, the mixes made in this study would be classified as follows: mixtures made with 2.5% and 3% straight fibers could be classified as enhanced ductility, 2% straight fibers would be strain hardening, and mixes 1% and 1.5% straight fibers, as well as 3% twisted fibers would qualify as strain softening. The remainder would be non-tensile UHPC. Based on this table, most projects with structural members made from UHPC would likely specify a strain hardening material. This would include highway closure strips which are designed to reduce the development length needed for mild steel reinforcement, columns or piles designed to experience bending stresses, and pretensioned members. Strain softening materials could be used in non-structural cases where crack width should remain small, such as in architectural applications, coatings for enhanced durability in seawater, or road overlays. The enhanced ductility class could be used if the designing engineer wants to rely heavily on the UHPC tensile strength in design. Because of the added cost, the enhanced ductility class would likely be used sparingly and on a case-by-case basis with the design structural engineer specifying desired values at specified stresses. This would ensure that the mix has been designed to perform well for its exact application.

Table 1-3: Recommended UHPC tension classes

Tensile Class	Maximum tensile stress (psi)	Maximum direct tensile stress after 0.005 in./in. strain (psi)	Maximum direct tensile stress after 0.010 in./in. strain (psi)
Non-tensile	-	-	-
Strain softening	800	400	-
Strain hardening	1000	900	-
Enhanced ductility*	1200	1100	900

*This class may also be used with specific requirements set by the structural engineer.

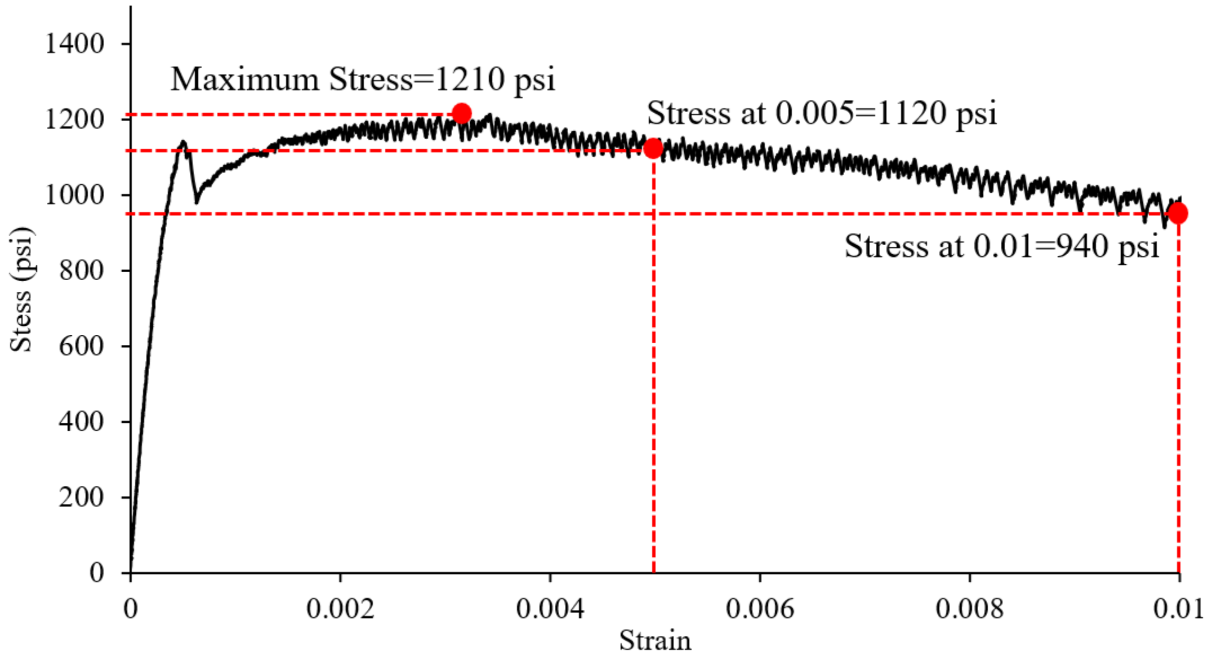

Figure 1-22: Example of qualification values taken from a direct tension test

The double punch or ASTM C1609 could be used as a suitable tensile strength quality control test for UHPC s because both adequately correlated to the direct tension. The flexure test provided better correlation to the direct tension test, but it is more time consuming and requires more expensive equipment than the double-punch test. Therefore, suggested quality control requirements for both tests are presented in **Error! Reference source not found.**, with the idea that only one test would be used, at the discretion of either the DOT or the testing lab. It is recommended that at least 3 specimens be required for testing and the average taken. The requirements for quality-control testing are slightly more lenient than the requirements for the quality-approval testing to account for testing variability because any mix design being tested in QC will already have been tested and approved with the more stringent QA direct tension test. For example, the mixture with 1.5% straight fibers would pass as a strain hardening material if it were tested with the flexure test in quality control. However, it would not have been approved as a strain hardening UHPC initially in the direct tension test. The purpose of the QC requirements is to be able to detect errors that may have occurred in a mix to cause a reduced tensile strength and toughness from what was expected. For example, the 2.5% straight fiber double-punch specimens were much weaker than expected based on the trends of other straight fiber double-punch tests. If the double-punch quality control test were performed on this mix, it would show that this mix could not be classified as enhanced ductility, even though the original mix design would have been approved for the enhanced ductility class by the direct tension test.

Table 1-4: Recommended UHPC quality-control requirements for tension classes

Tensile Class	Maximum Flexural Stress (psi)	Flexure stress at l/150 (psi)	Maximum Double-punch stress (psi)	Double-punch toughness (psi·in.)
Non-tensile	-	-	-	-
Strain softening	1800	1000	800	90
Strain hardening	2300	2000	1000	130
Enhanced ductility	2500	2200	1200	200

It is recommended that a round-robin study is performed across multiple labs and technicians before implementing the simplified double punch test.

1.5. References

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APPENDIX A

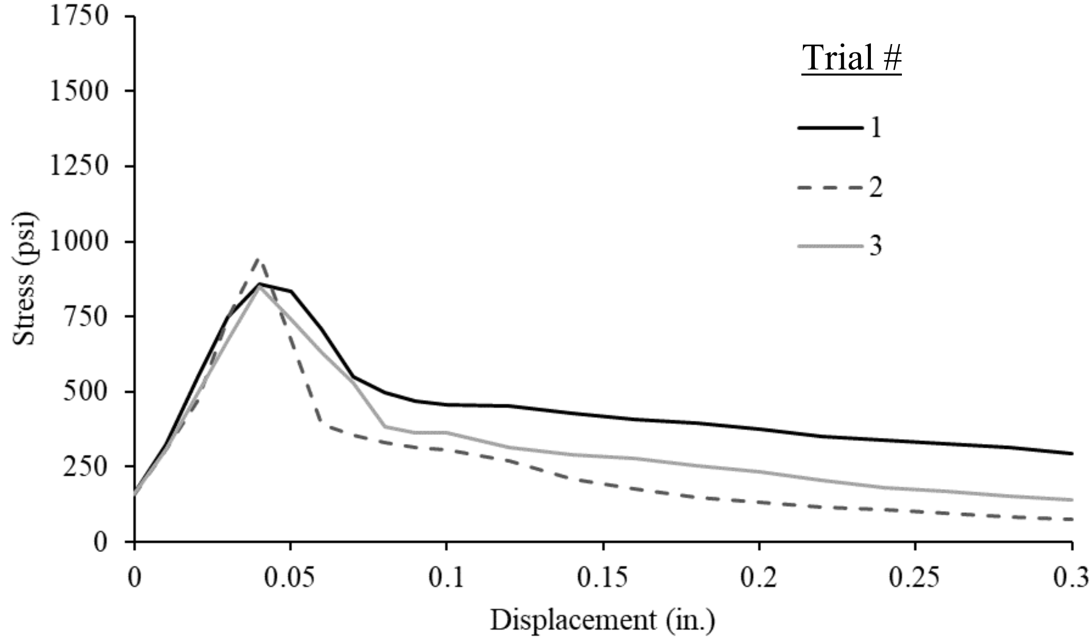

Figure A-1: Double-punch results for 1% straight fiber specimens

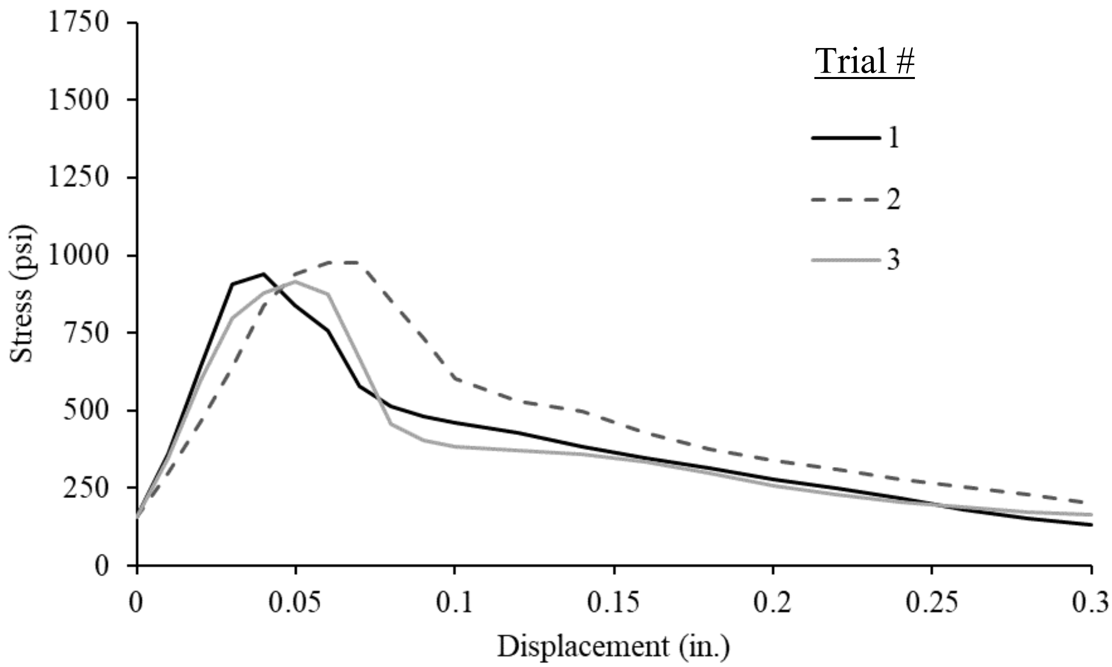

Figure A-2: Double-punch results for 1.5% straight fiber specimens

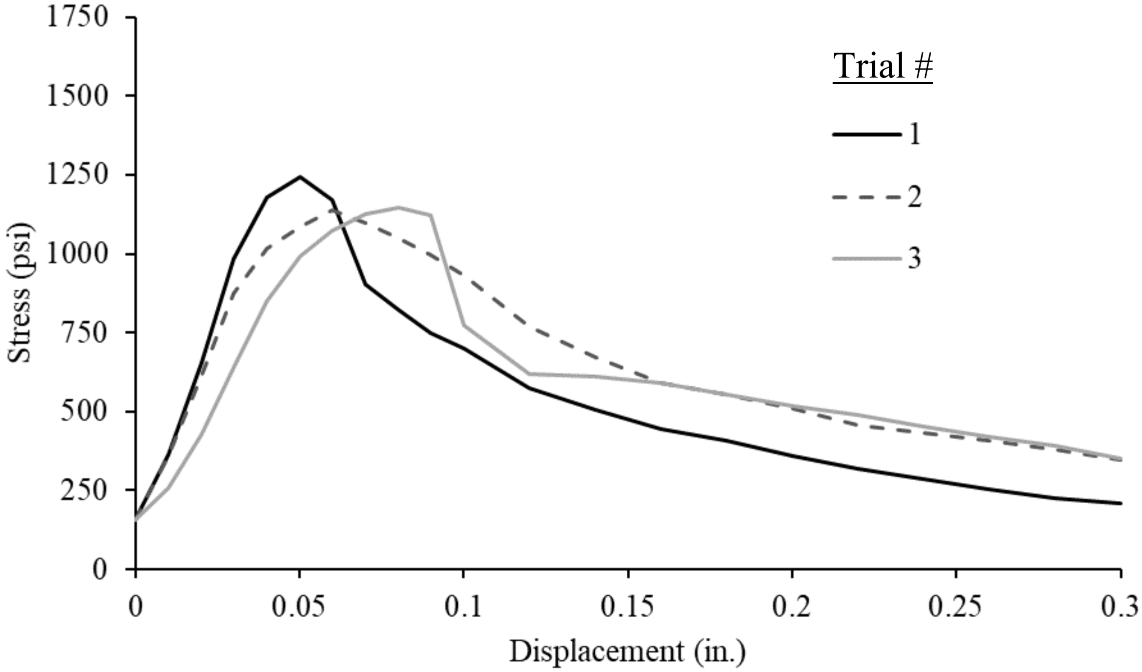

Figure A-3: Double-punch results for 2% straight fiber specimens

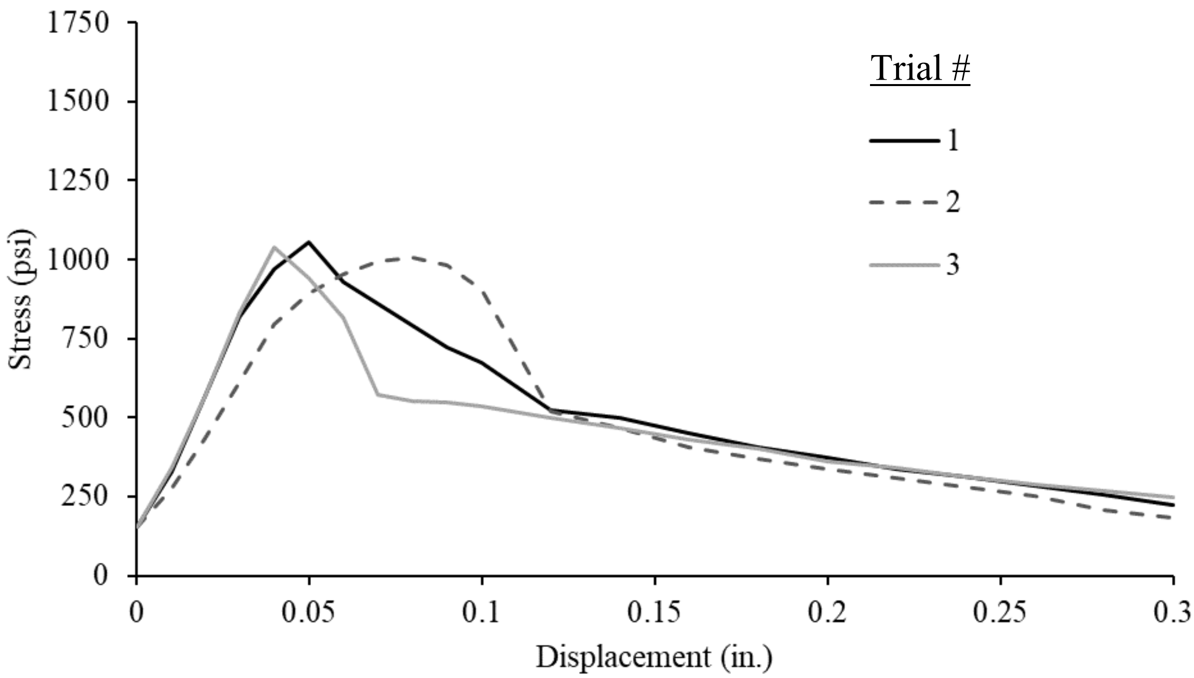

Figure A-4: Double-punch results for 2.5% straight fiber specimens

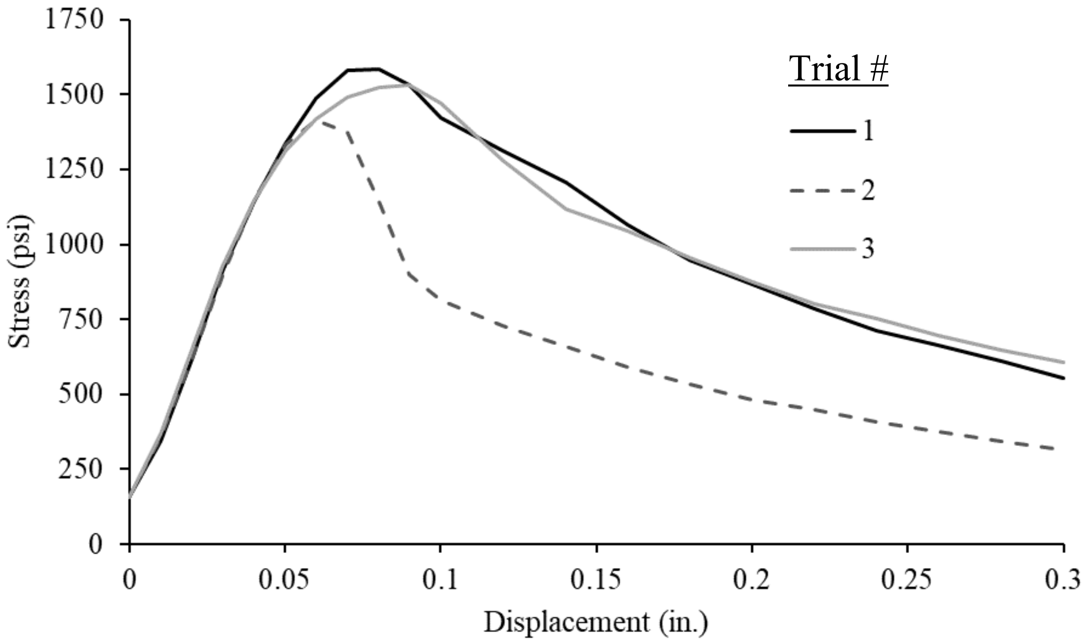

Figure A-5: Double-punch results for 3% straight fiber specimens

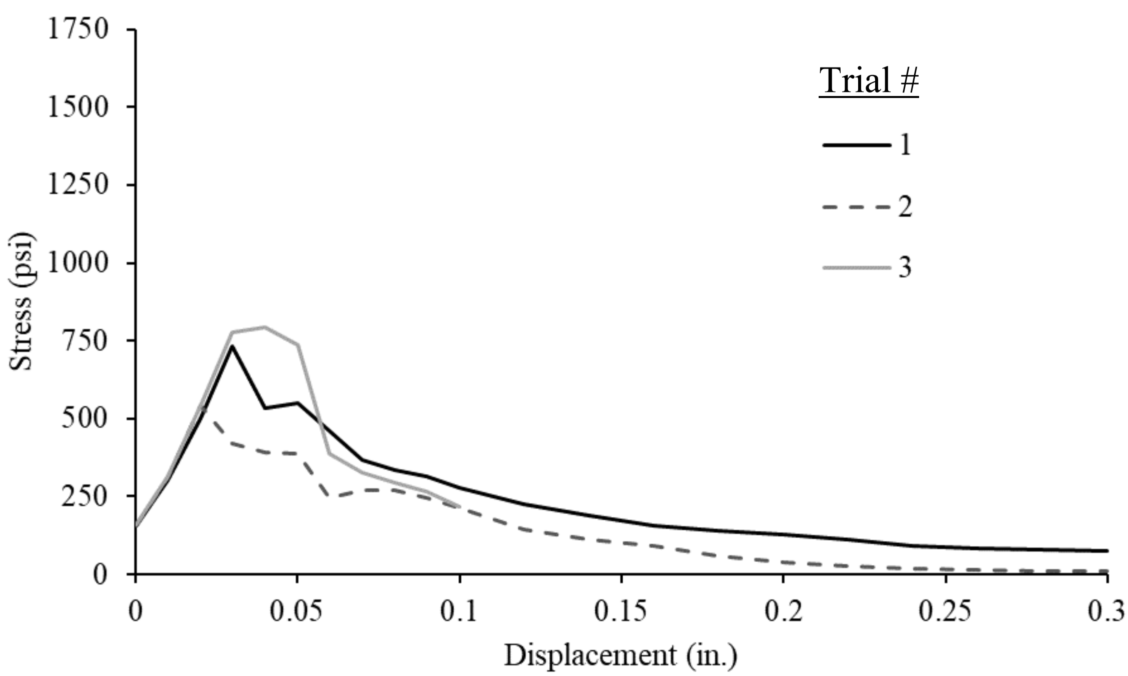

Figure A-6: Double-punch results for 1% twisted fiber specimens

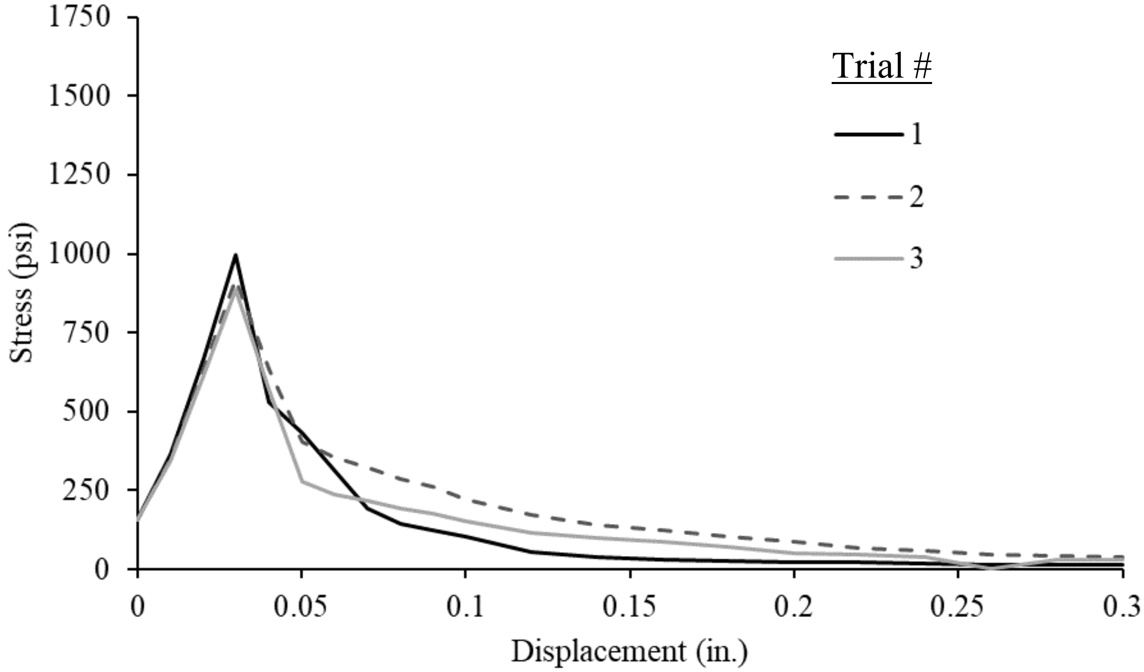

Figure A-7: Double-punch results for 1.5% twisted fiber specimens

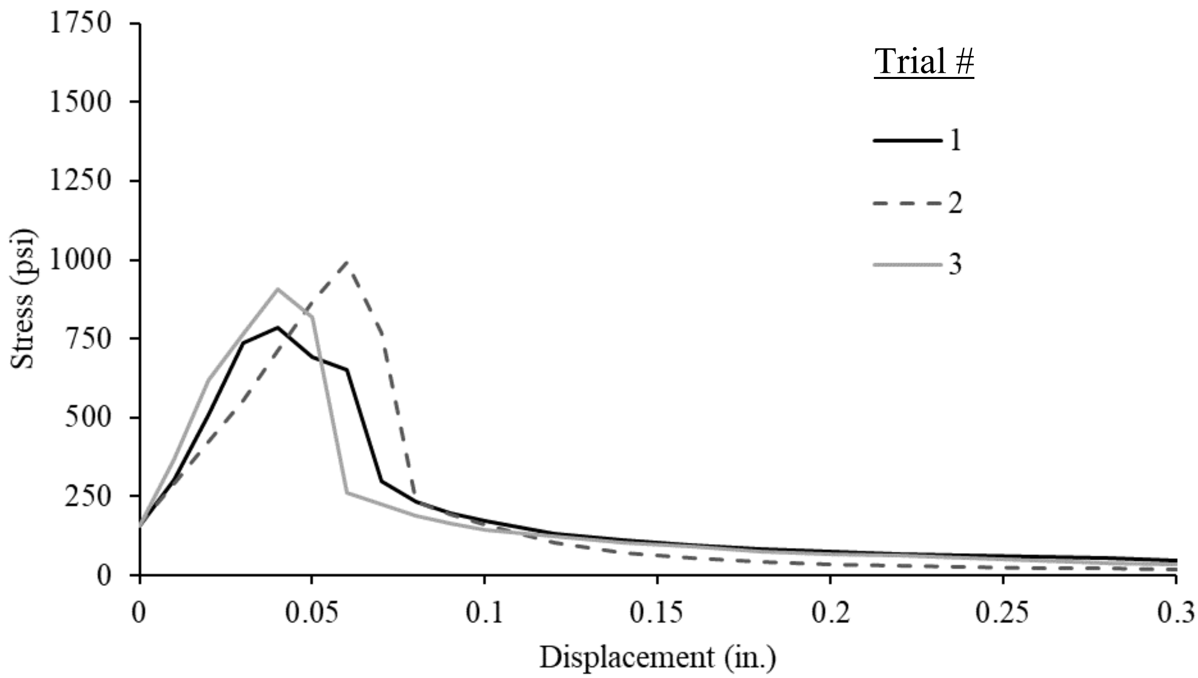

Figure A-8: Double-punch results for 2% twisted fiber specimens

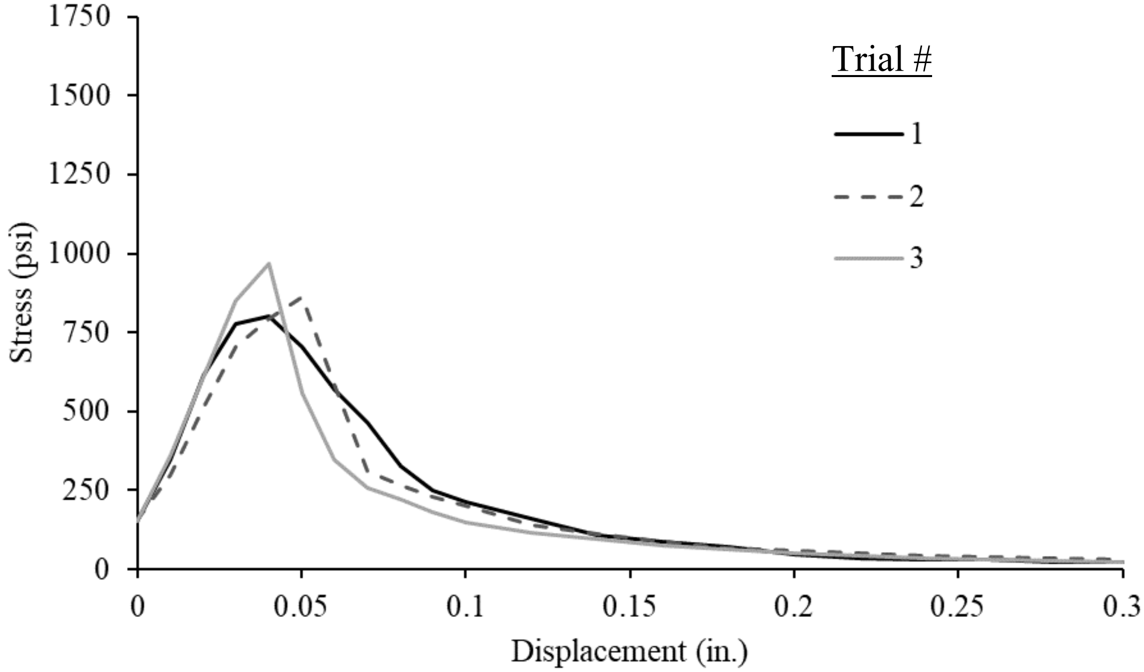

Figure A-9: Double-punch results for 2.5% twisted fiber specimens

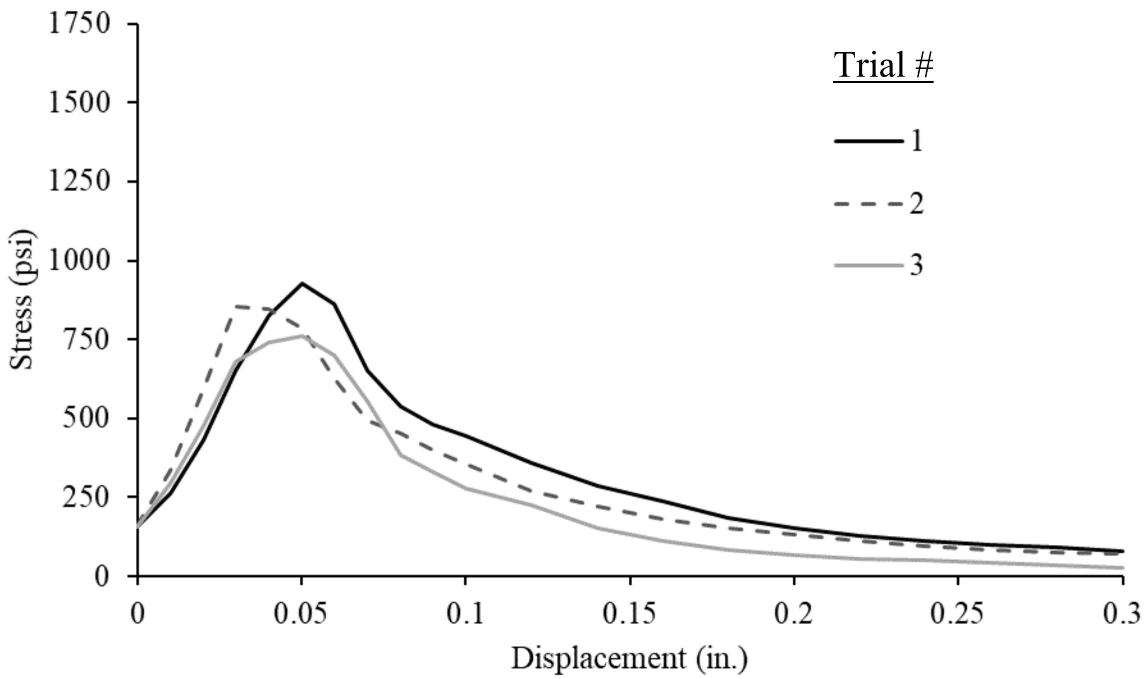

Figure A-10: Double-punch results for 3% twisted fiber specimens

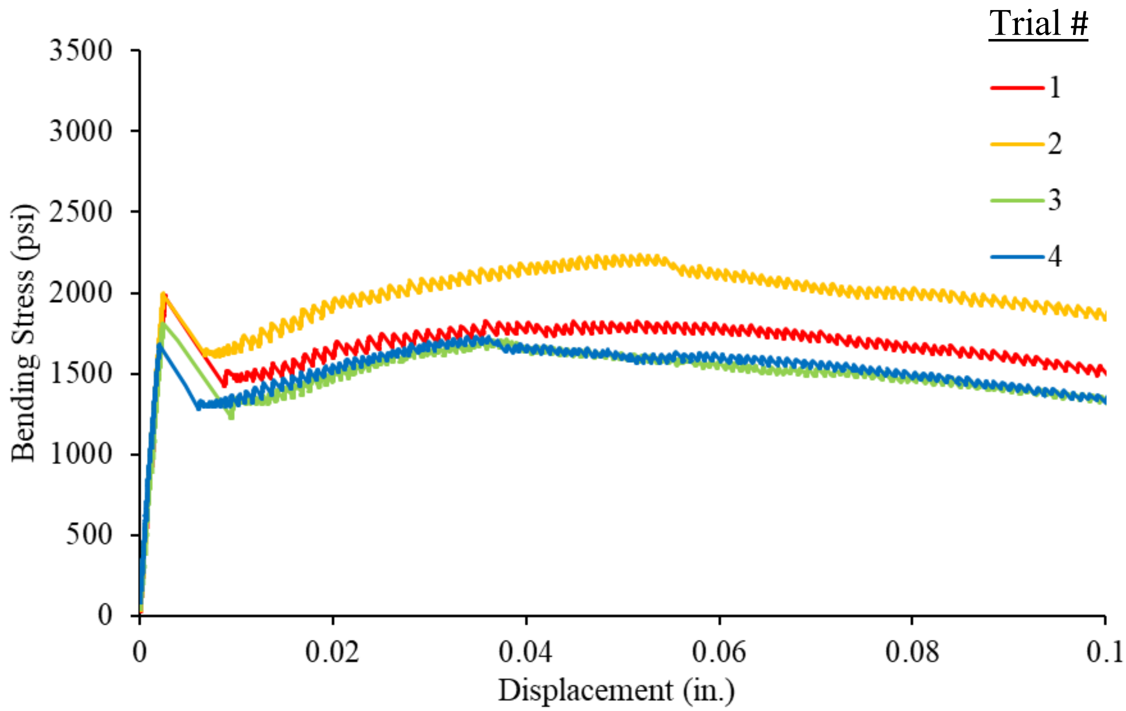

Figure A-11: Flexure results for 1% straight fiber specimens

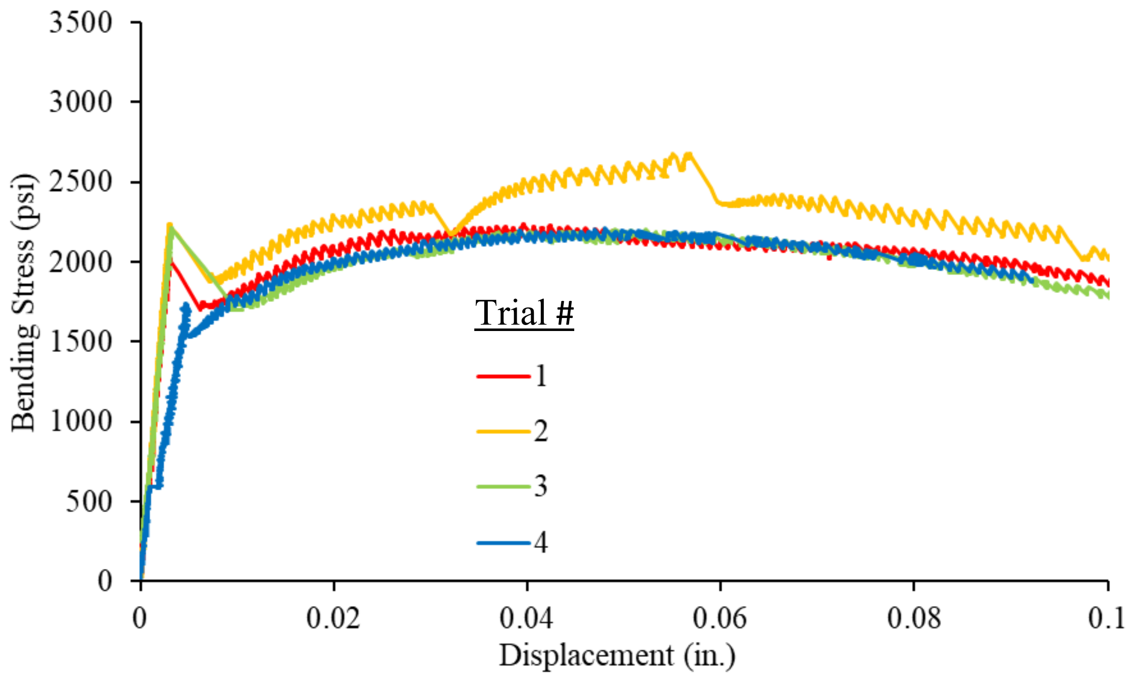

Figure A-12: Flexure results for 1.5% straight fiber specimens

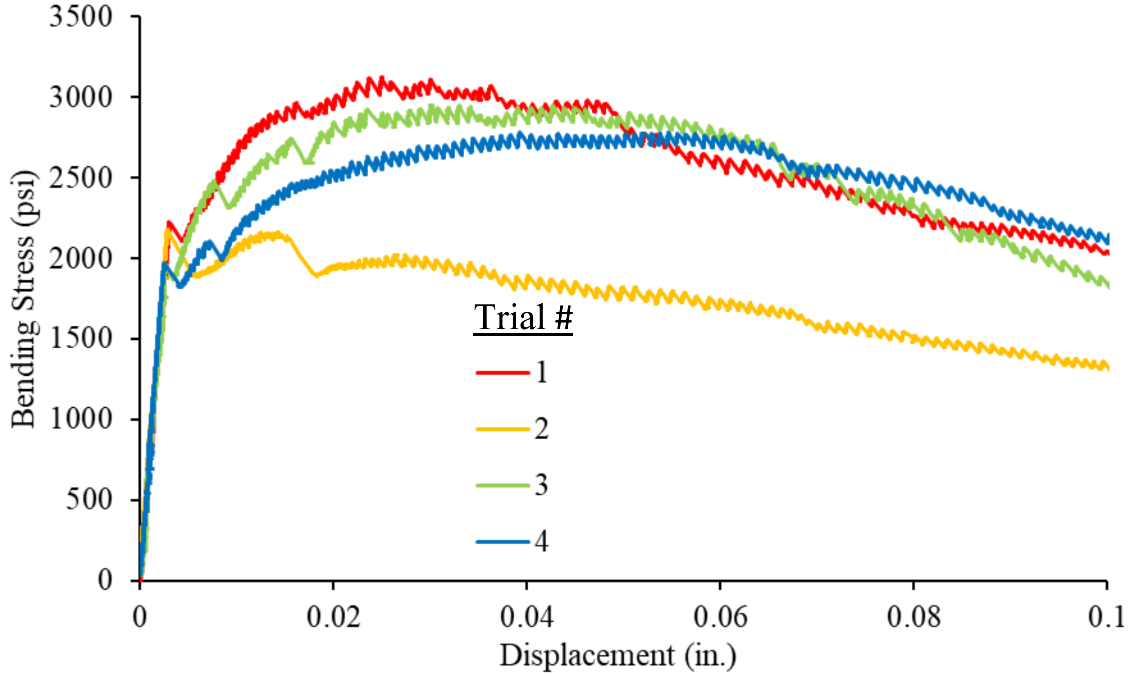

Figure A-13: Flexure results for 2% straight fiber specimens

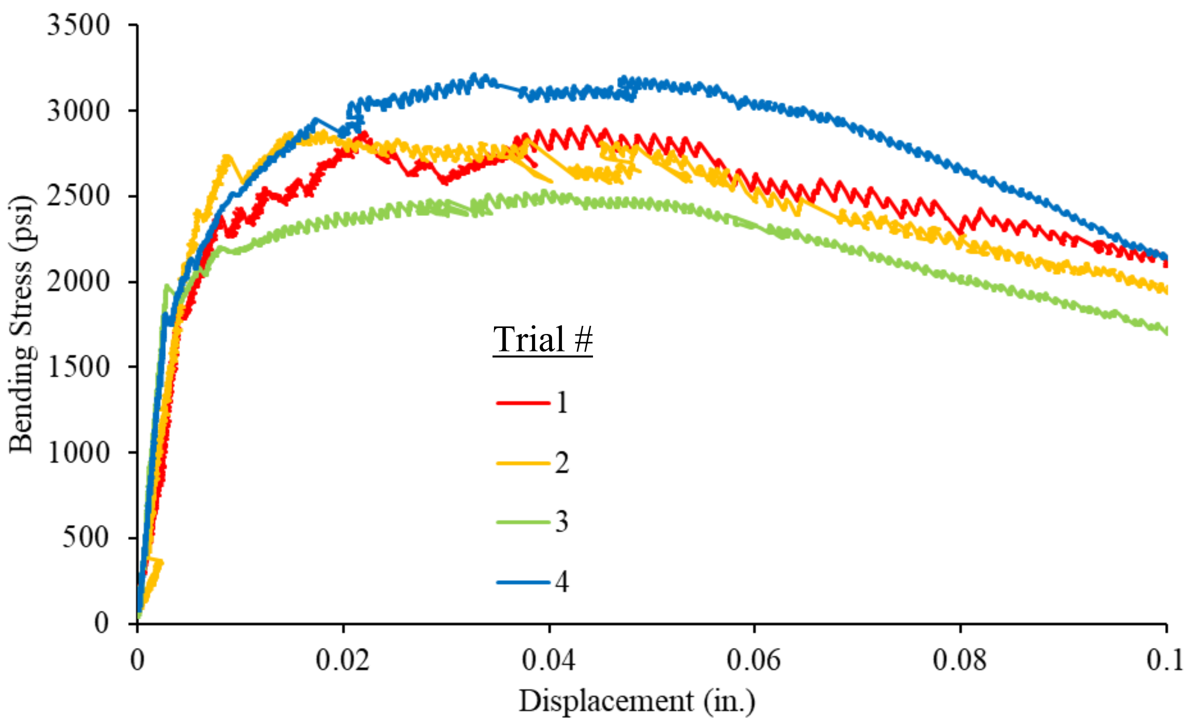

Figure A-14: Flexure results for 2.5% straight fiber specimens

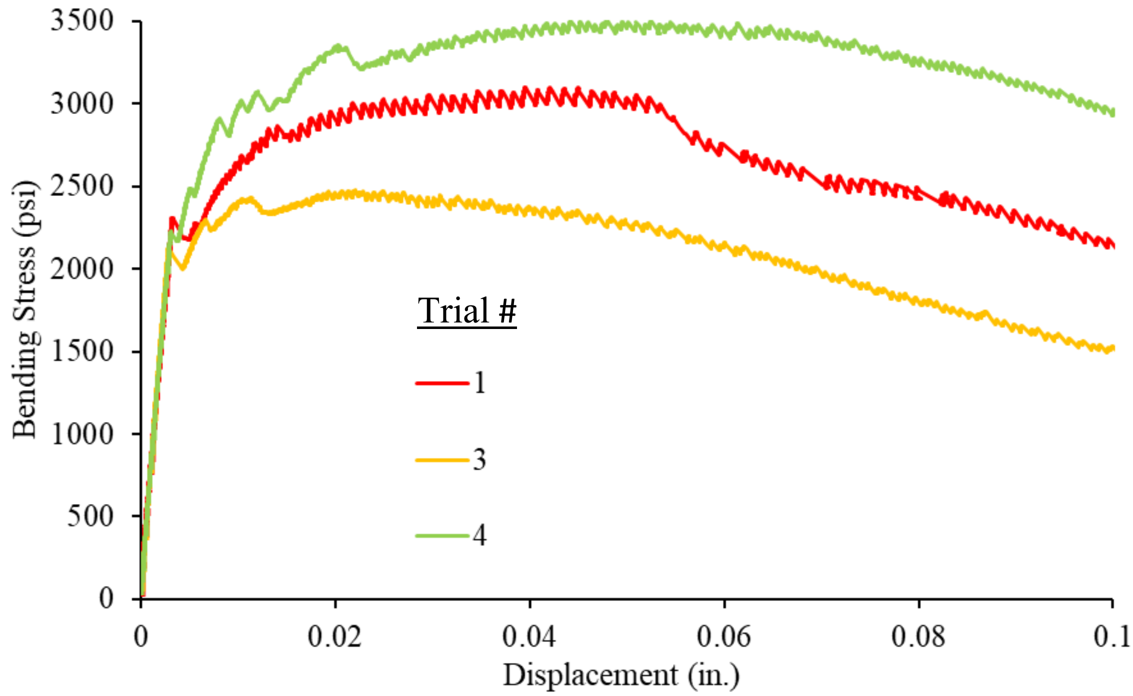

Figure A-15: Flexure results for 3% straight fiber specimens

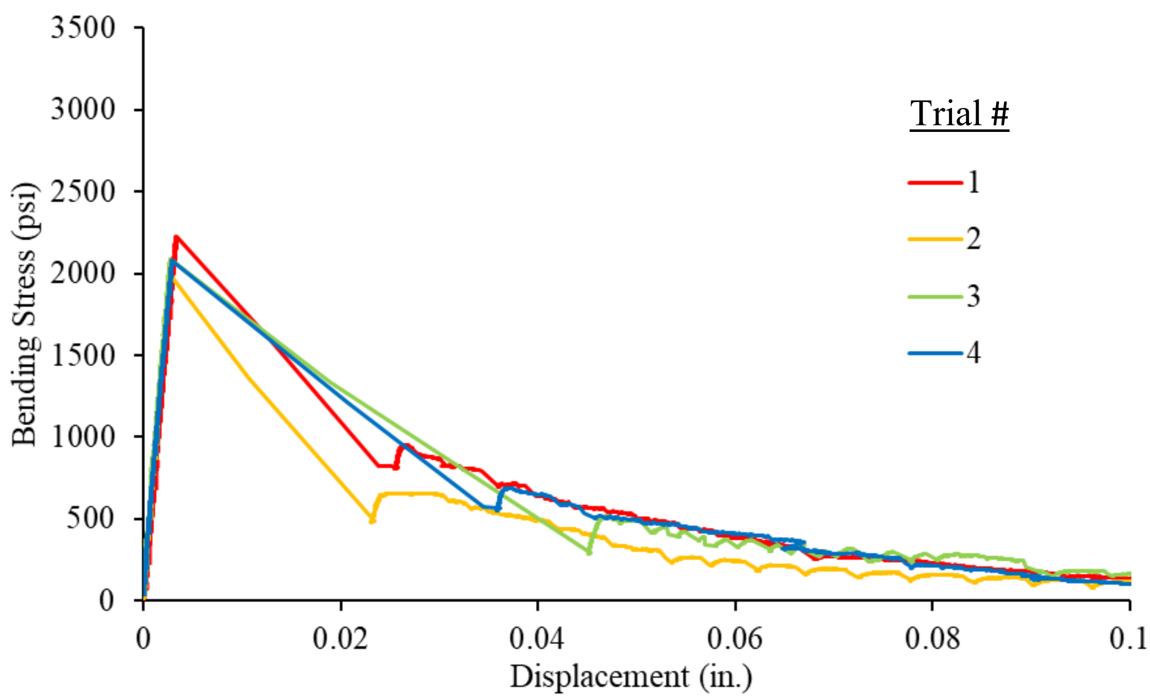

Figure A-16: Flexure results for 1% twisted fiber specimens

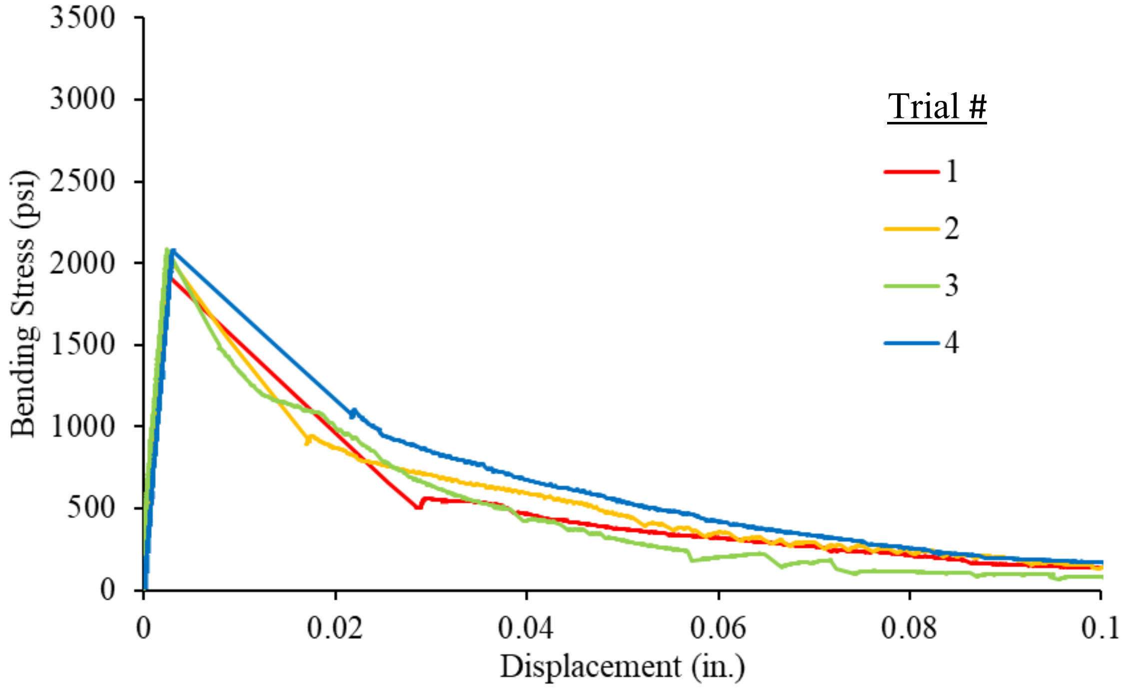

Figure A-17: Flexure results for 1.5% twisted fiber specimens

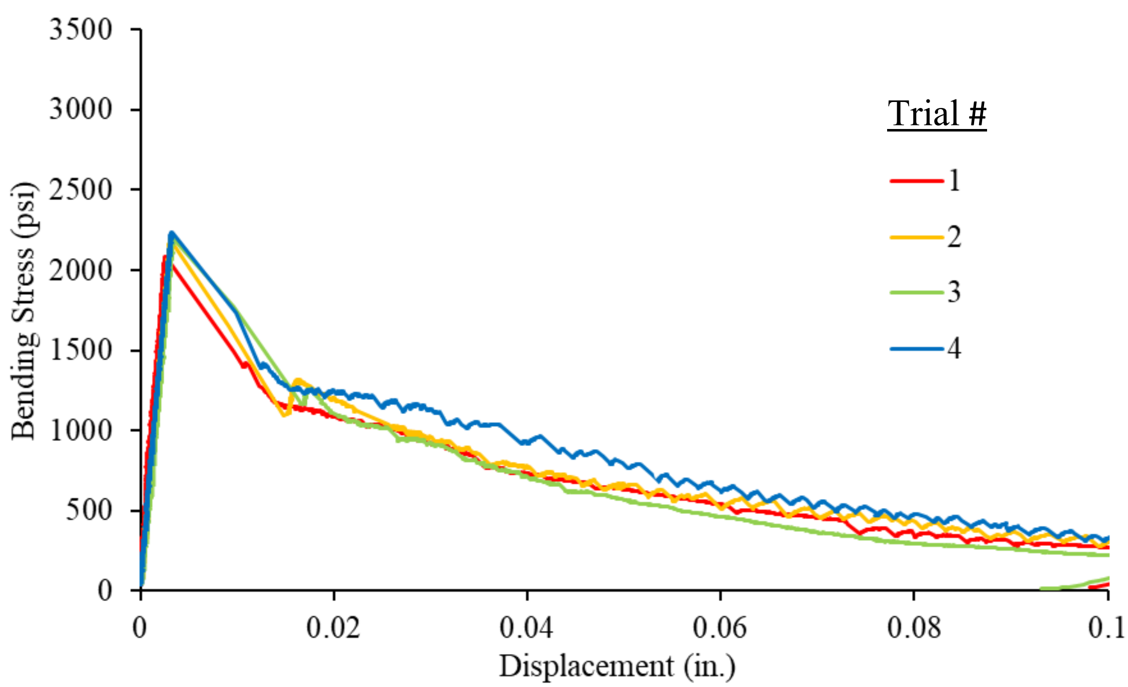

Figure A-18: Flexure results for 2% twisted fiber specimens

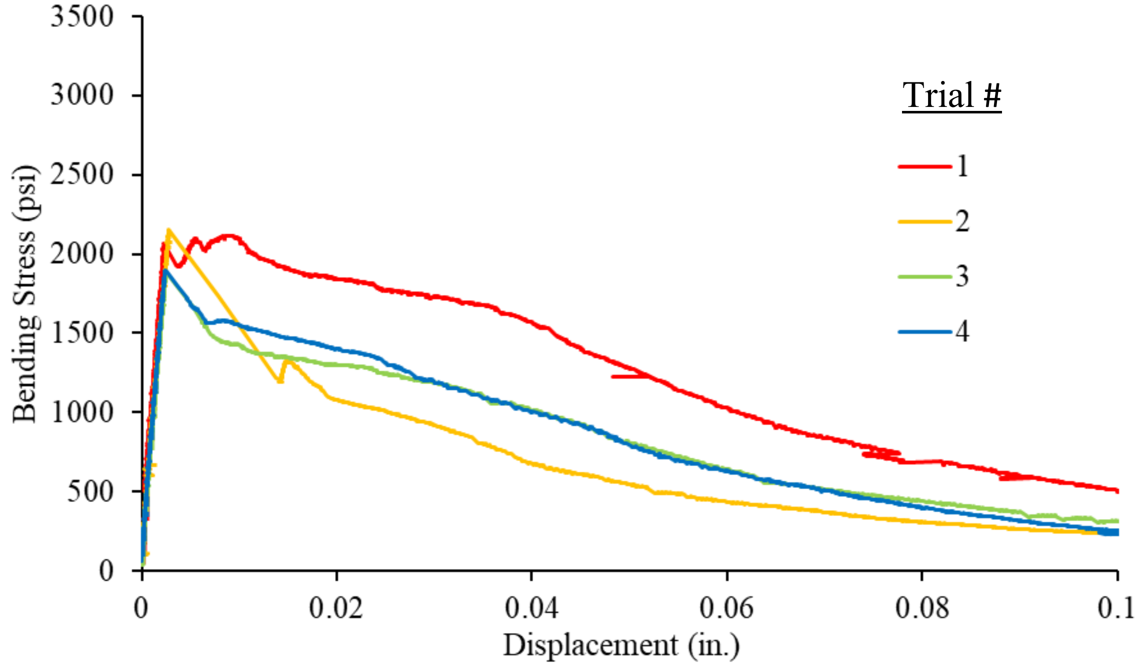

Figure A-19: Flexure results for 2.5% twisted fiber specimens

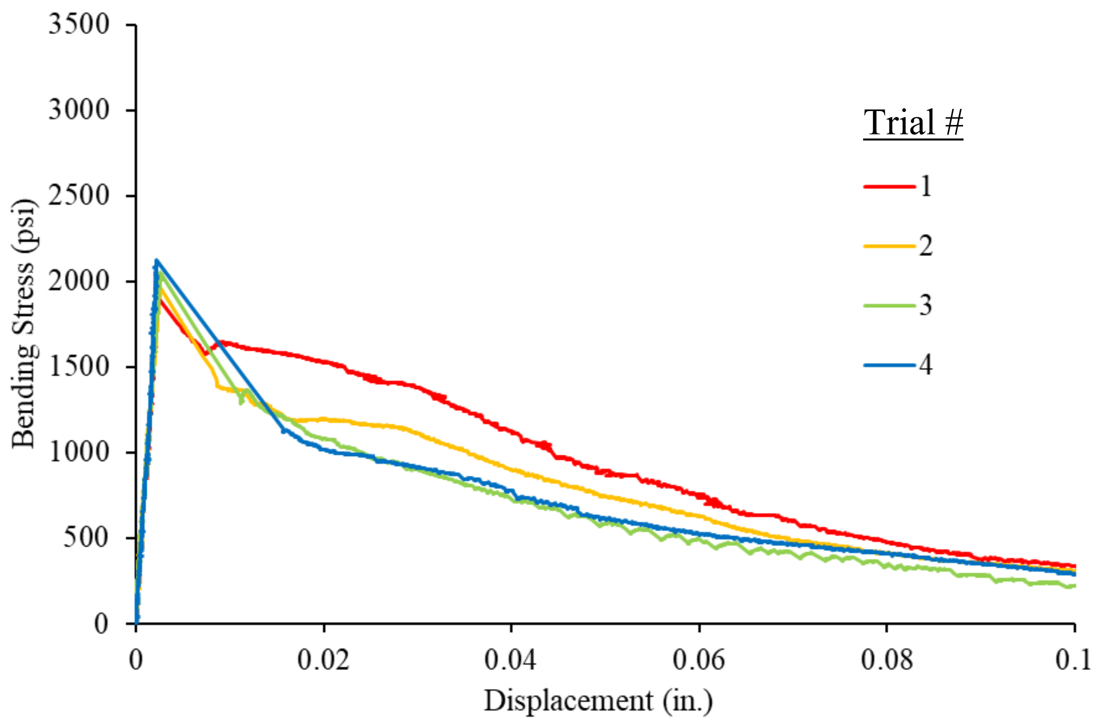

Figure A-20: Flexure results for 3% twisted fiber specimens

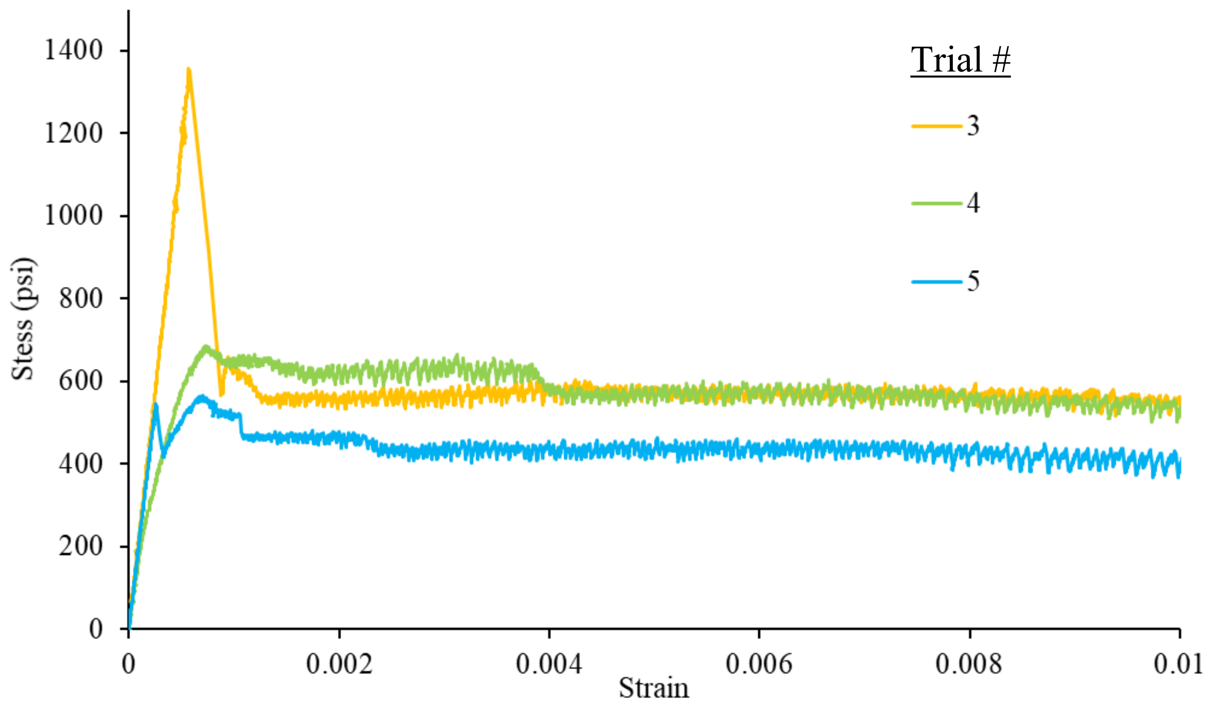

Figure A-21: Direct tension results for 1% straight fiber specimens

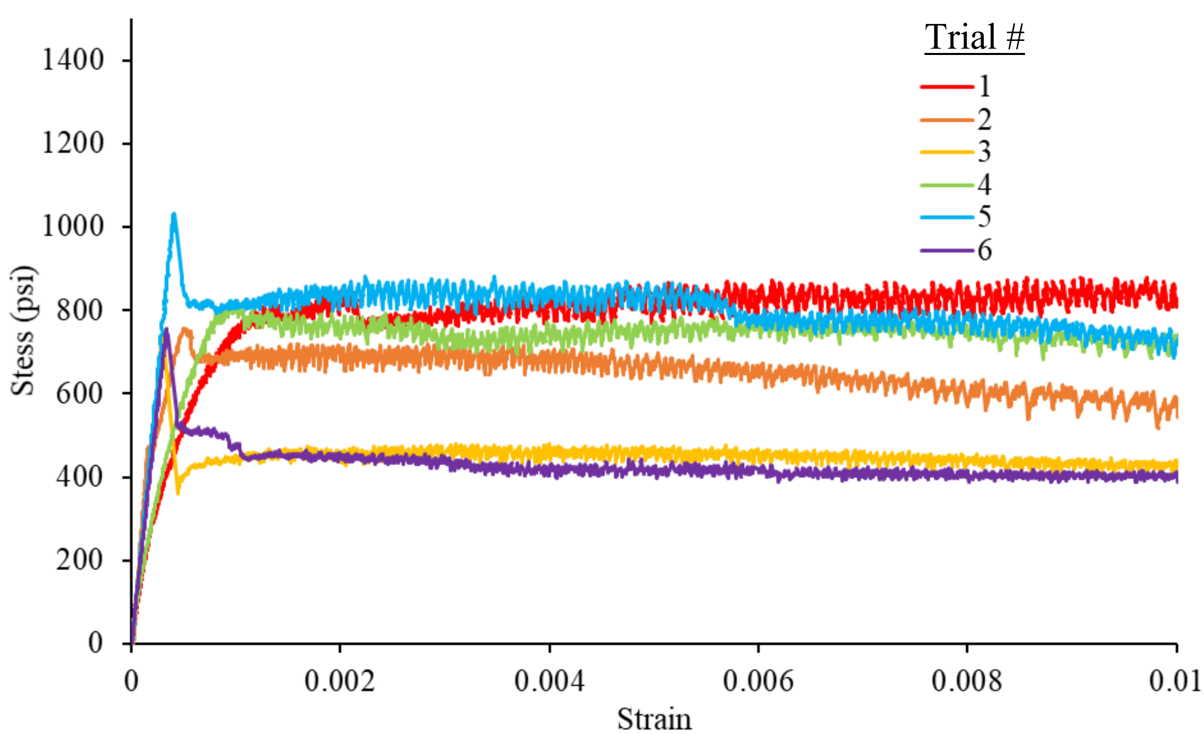

Figure A-22: Direct tension results for 1.5% straight fiber specimens

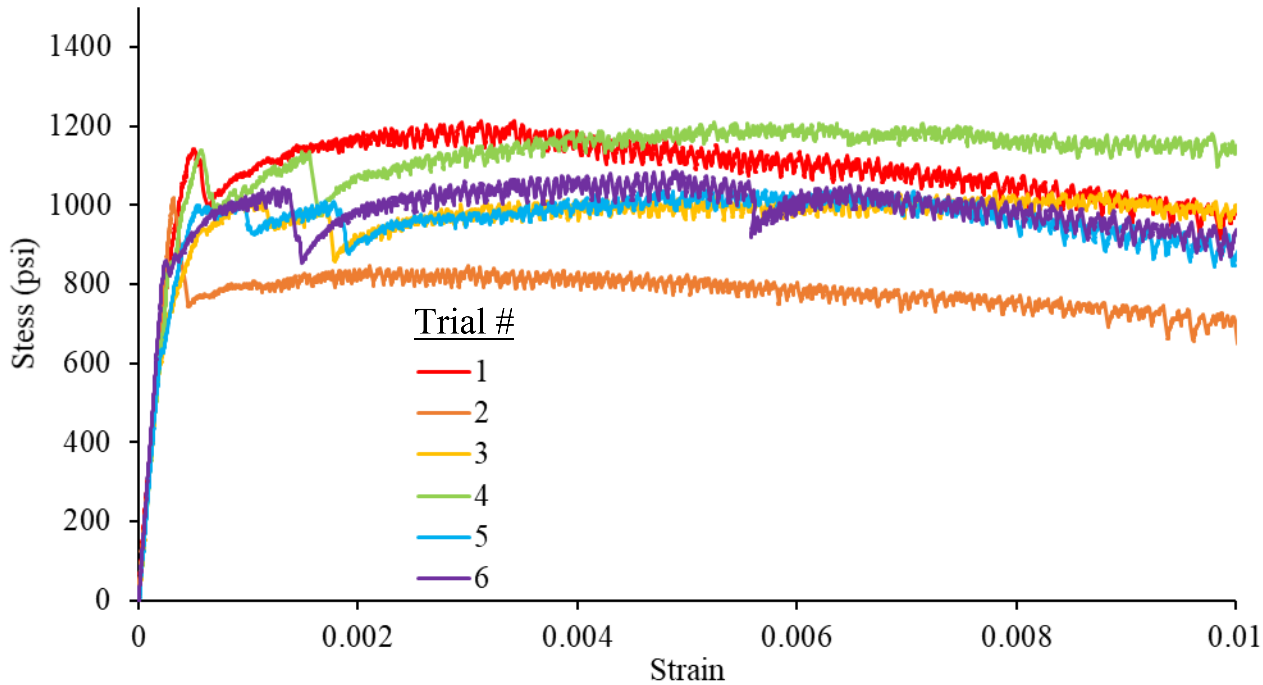

Figure A-23: Direct tension results for 2% straight fiber specimens

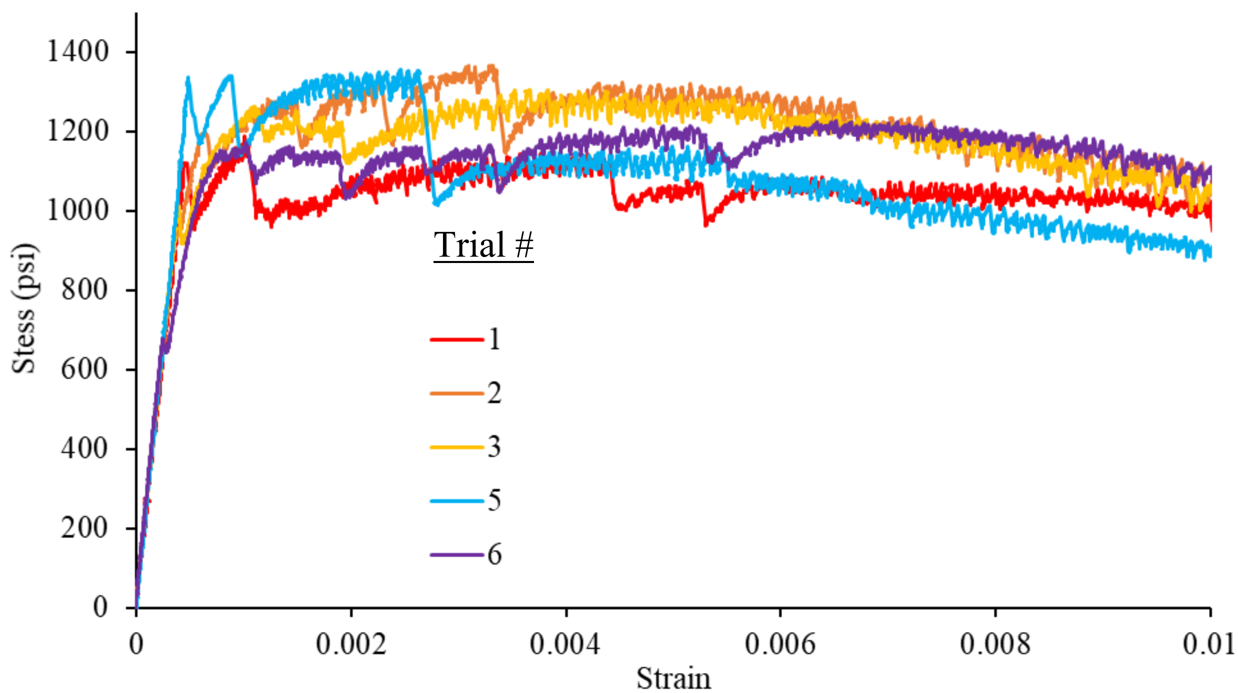

Figure A-24: Direct tension results for 2.5% straight fiber specimens

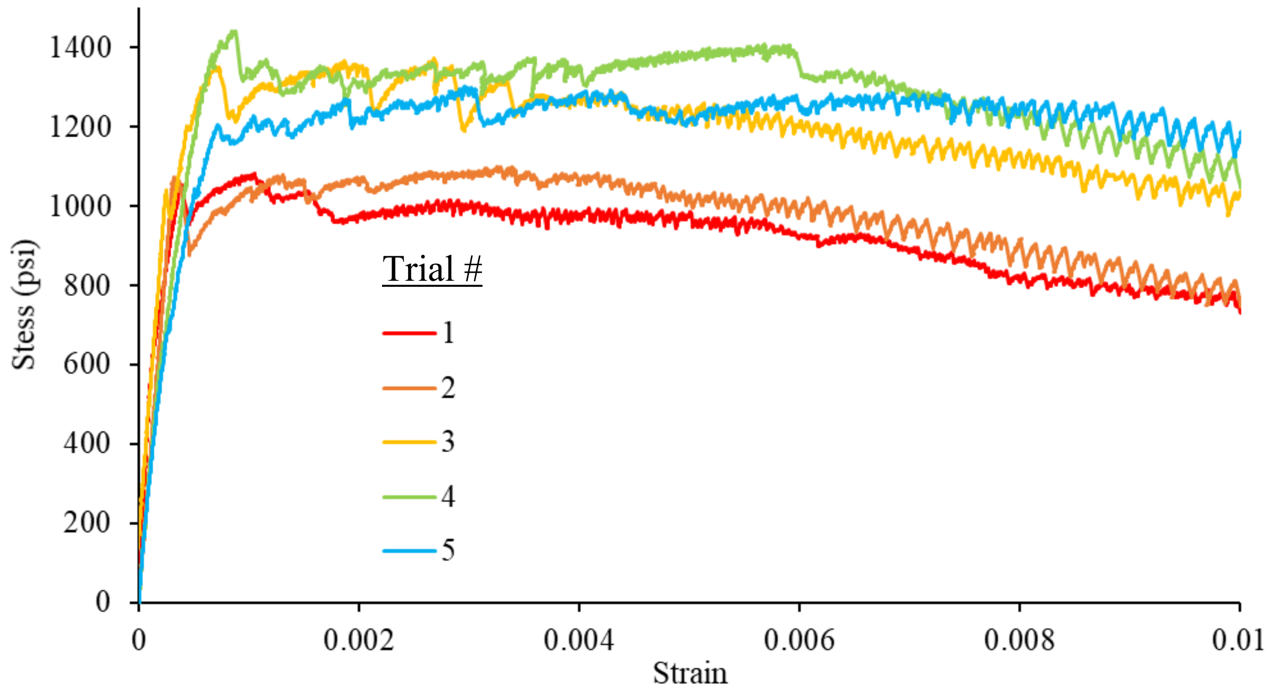

Figure A-25: Direct tension results for 3% straight fiber specimens

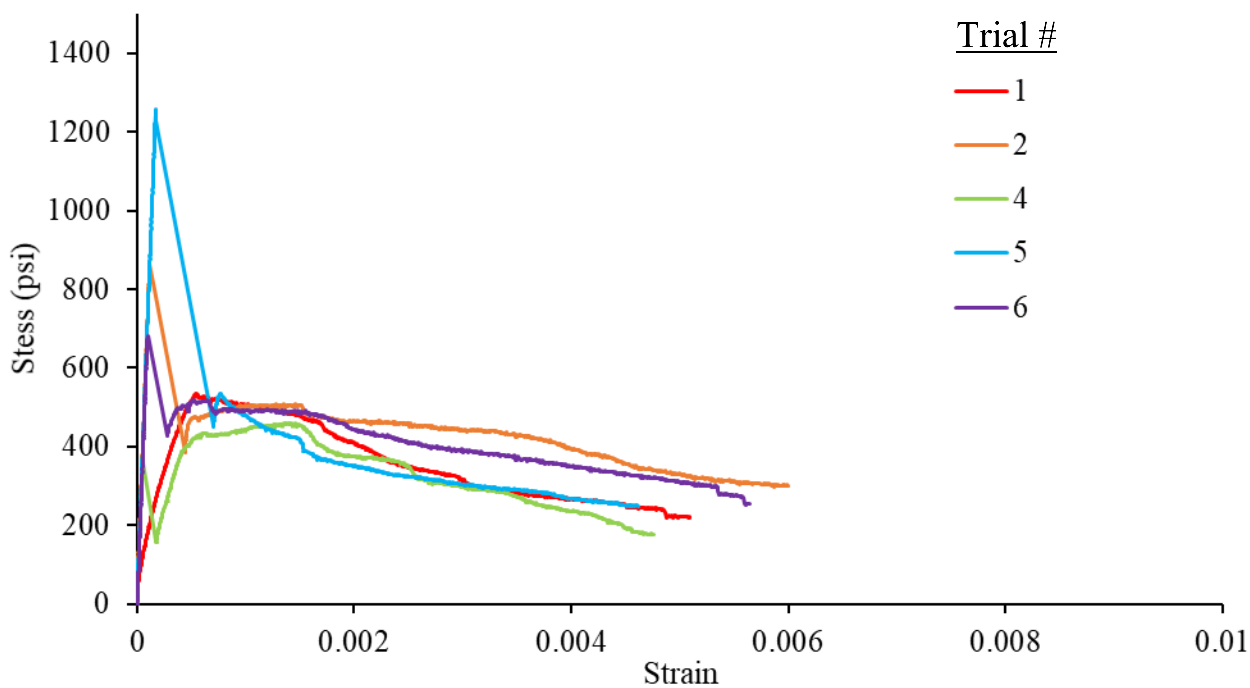

Figure A-26: Direct tension results for 1% twisted fiber specimens

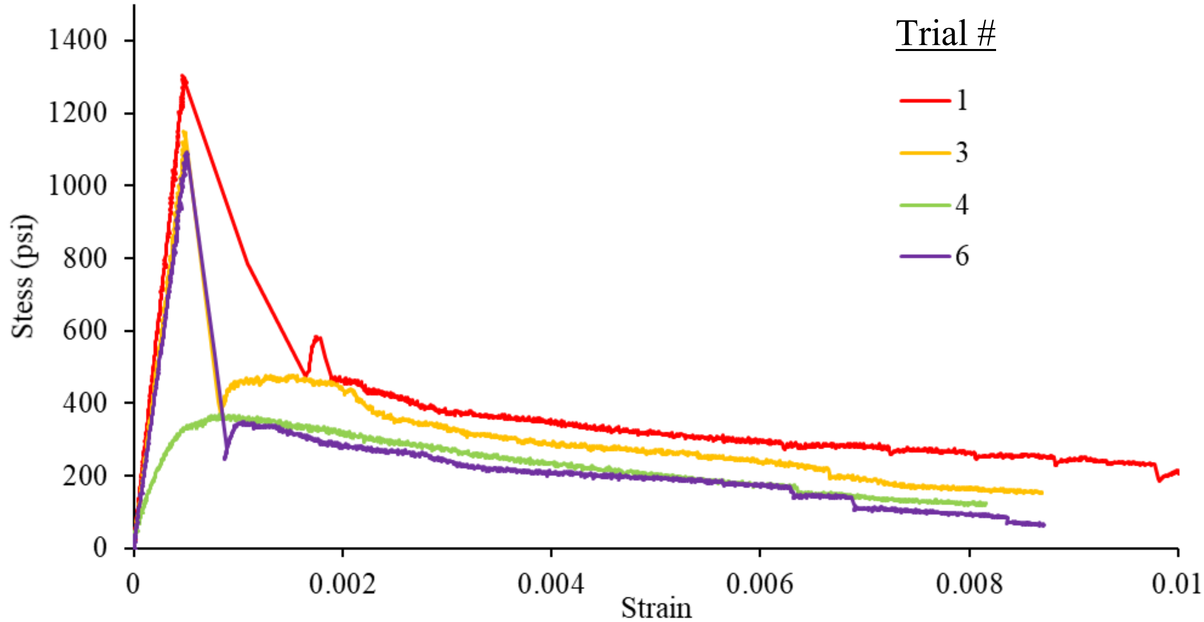

Figure A-27: Direct tension results for 1.5% twisted fiber specimens

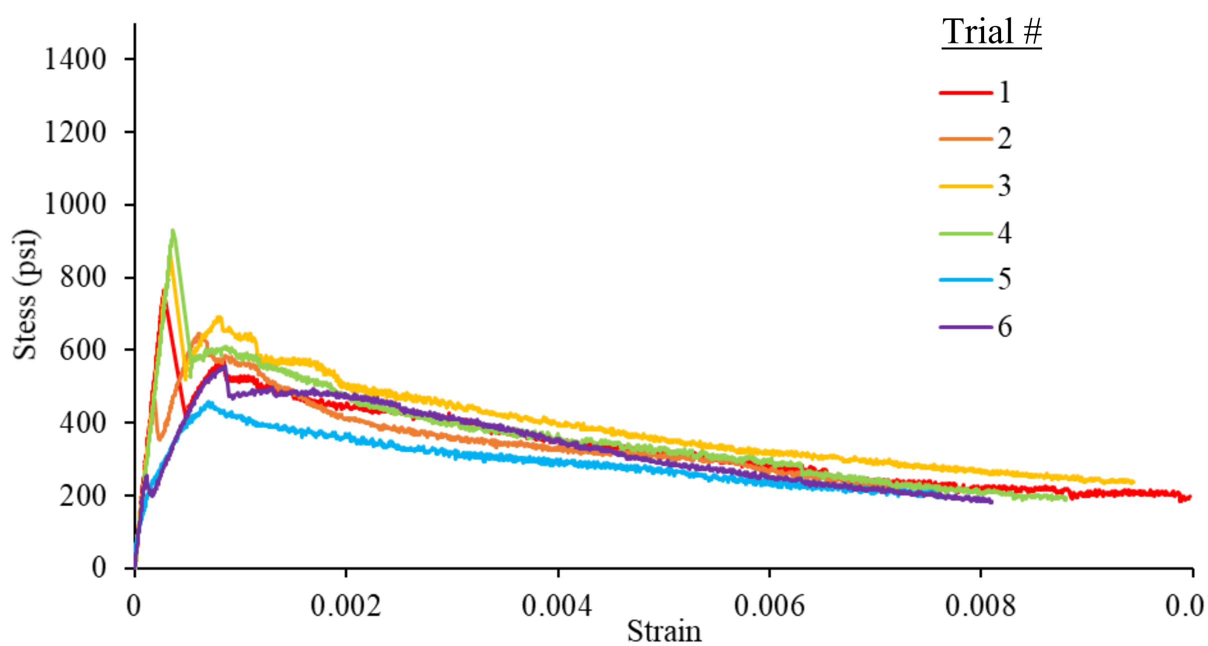

Figure A-28: Direct tension results for 2% twisted fiber specimens

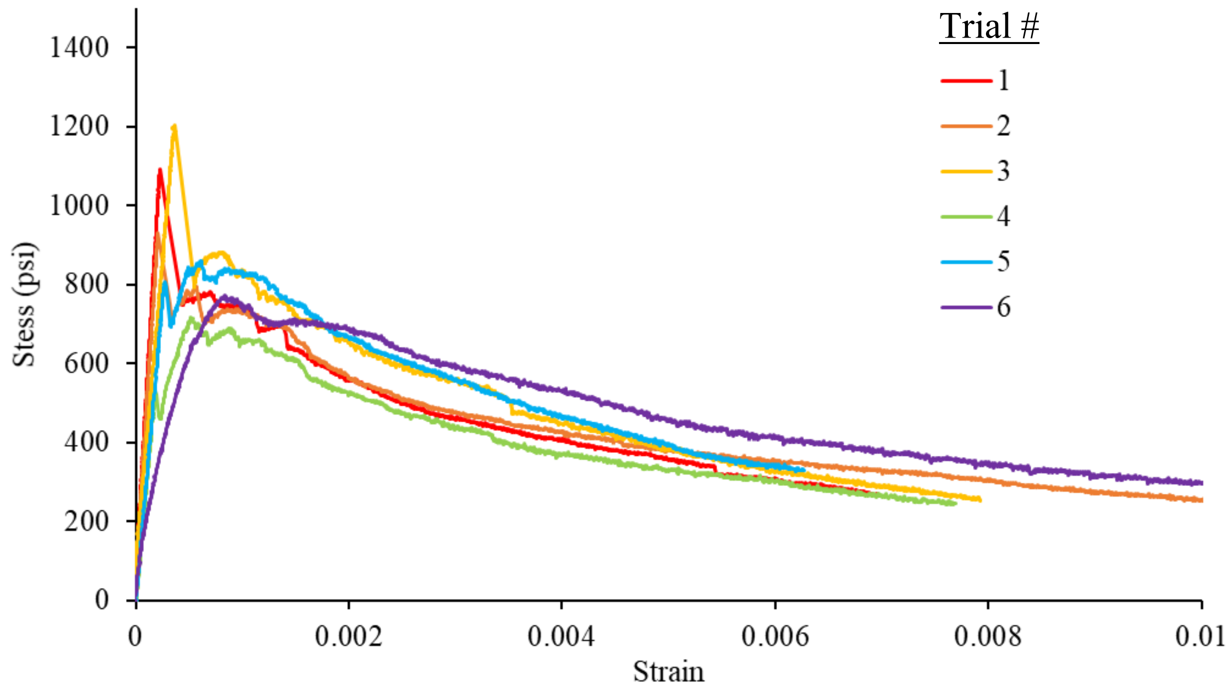

Figure A-29: Direct tension results for 2.5% twisted fiber specimens

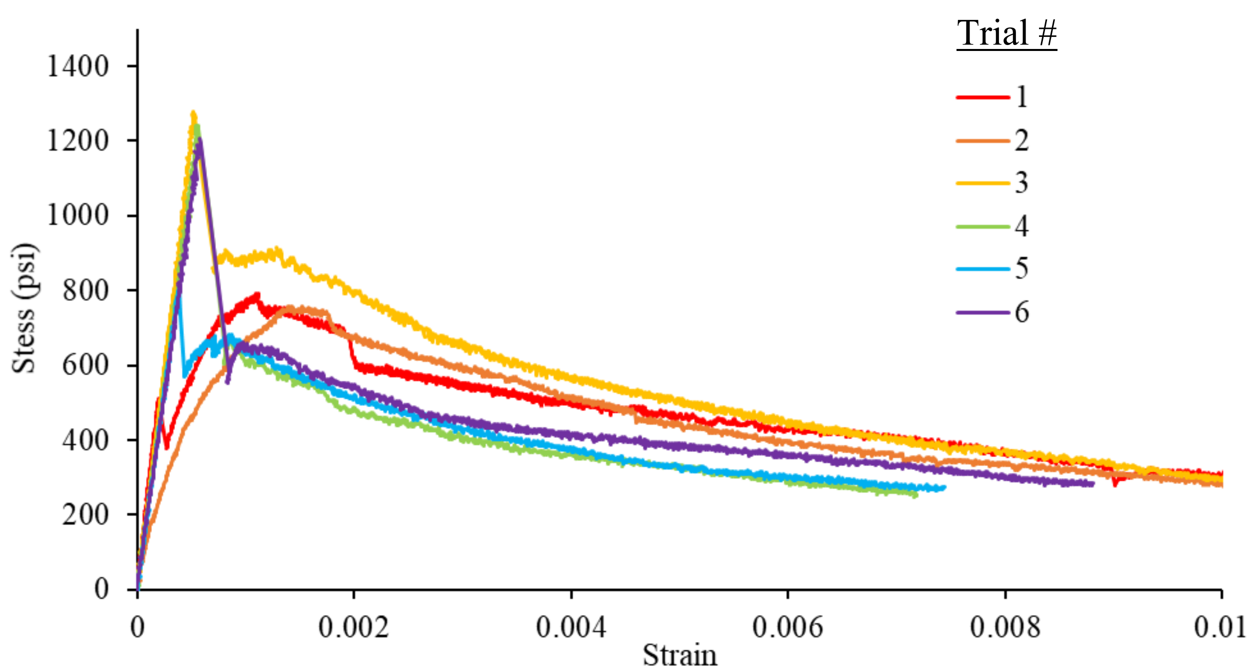

Figure A-30: Direct tension results for 3% twisted fiber specimens