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Measurement of Average Tensile Force for Individual Steel Fiber Using New Direct Tension Test

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TECHNICAL NOTE

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ABSTRACT

The use of steel-fiber reinforcement as an alternative to conventional reinforcement of various concrete structures has been limited in the construction industry. This is because of the fact that, unlike traditional reinforcement, the performance characterization of steel-fiber concrete is not standardized, because the fibers are distributed throughout the concrete section. Whereas direct tensile resistance is the performance measurement required for design, the steel-fiber industry has yet to actively employ direct tensile testing of steel fibers. The tensile response of steel-fiber-reinforced concrete has been investigated. The primary purpose of this paper is to present a robust new direct tension test method. This method is able to determine the uniaxial tensile response of steel-fiber-reinforced concrete. The method uses a three-dimensional "hourglass"-shaped tapered specimen. This paper also focuses on developing a practical method to determine the average tensile force per fiber.

Keywords

tension testing, fiber-reinforced concrete, steel fibers, TSMR, twisted steel micro rebar

Introduction

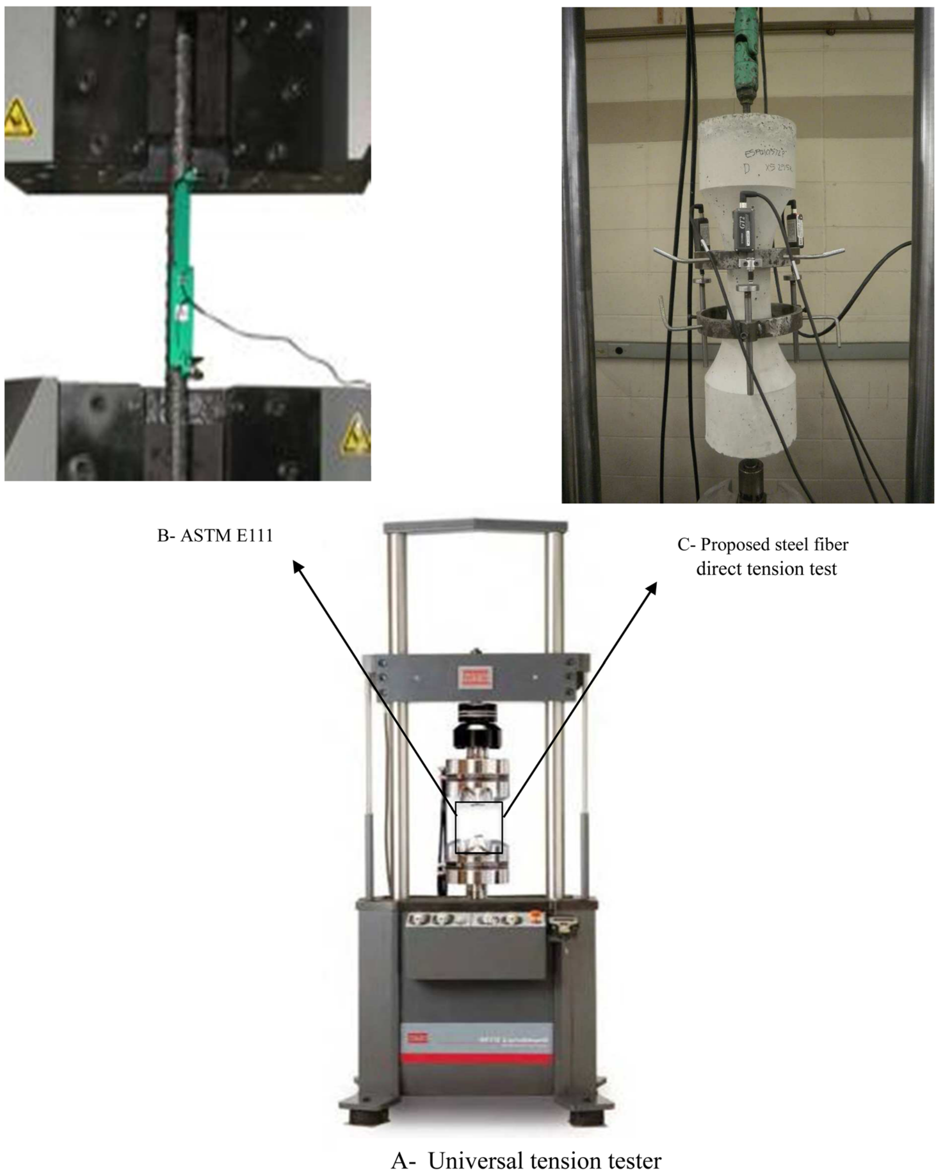
Traditional steel-fiber design and performance evaluation focused on the use of flexural test standards to measure the tensile behavior of steel-fiber-reinforced concrete in terms of residual flexural stress [1–4]. The residual flexural stress, which is determined from the load-displacement curve or load-deflection curve is obtained through the utilization of a three- or four-point flexural beam test [5–7]. Tensile resistance is then derived by assuming a relationship between the residual flexural stress (which only exists in linear elastic materials and is invalid after a crack forms) and direct tensile stress [8]. A multiplier of 0.37 and 0.45 (which assumes linearly decreasing load as crack width increases) is typically used to relate the flexural stress in beams with large cracks (3.5 mm) to direct tensile strength [9]. Beam testing is also plagued with so called "size effect," the non-scalability of results to larger or smaller sections and/or cross correlation of crack size, fiber length, and specimen size on the results [9]. As a result, engineers are less confident in specifying steel fiber for their projects.

The tensile response of steel-fiber-reinforced concrete has been investigated by researchers [1–4]. The primary purpose of this paper is to present a robust test method that is able to determine the uniaxial tensile response of steel-fiber-reinforced concrete. The method uses a three-dimensional "hourglass"-shaped tapered specimen. The primary purpose of this paper is to present a robust test method that is able to determine the uniaxial tensile response of steel-fiber-reinforced concrete. This paper also focuses on developing a practical method to determine the average tensile force per fiber [10]. The possibility of using the results in section analysis is outside of the scope of this paper.

The proposed direct tensile testing (DTT) is routinely used to measure the tensile properties of steel reinforcing bars. This procedure is performed under ASTM E111-04 [11] and is shown in **Fig. 1** below. This test method determines the yield strength, Young's modulus, tangent modulus, and chord modulus of the reinforcing bar. Using the same concept, a new DTT

FIG. 1

ASTM E111-04 [11] versus the new direct tension test.



method was developed to accurately capture the tensile response of steel-fiber-reinforced concrete. This method uses a three-dimensional "hourglass"-shaped tapered specimen. In addition, the average tensile force per fiber can be determined.

This new approach is unique because it resolves the problem of variable fiber performance because of specimen size and loading geometry. This is accomplished by isolating the two primary variables of fiber performance in concrete, which are force per fiber and fiber distribution. Using this test method, the distribution variable can be tested independently of the force variable. Separating the distribution variable allows for less expensive testing of smaller specimens without compromising accuracy. The fiber distribution is outside of the scope of this paper.

This paper encloses the details of the proposed direct tension test, specimen preparation, test preparation, and test procedure. It also includes machine specifications, reporting specifications and results, and a discussion of experimental results of the new DTT method using twisted steel micro rebar (TSMR).

Proposed Test Method

The newly developed direct tension test using a three-dimensional "hourglass"-shaped tapered specimen addresses the following concerns:

- Enables the investigation of the tensile response of steel fibers before and after formation of a dominate crack.
- Encourages the development of a crack within the gauge length without the need for notching.
- Eliminates the variation in results because of support conditions.
- Eliminates inconsistency in fiber distribution that typically occurs in fiber beam tests.

The new three-dimensional direct tensile test was developed to accurately capture force per fiber. A three-dimensional "hourglass"-shaped specimen, shown in **Fig. 2**, has been designed with a very slight taper. The taper to the 50-mm (2-in.) gauge length is designed to minimize stress variation while encouraging the development of the first crack to occur at the center of the specimen. The test specimen was analyzed with two different taper angles, 0.5 degree and 1 degree. It was also analyzed without a taper angle. This was performed using finite element analysis, and **Fig. 2** shows the location of the analyzed gauge section. The stresses were normalized by the maximum stress and expressed as a percentage shown in **Figs. 3–5**. **Fig. 3** shows that, without the taper, the high stress is located in the transition region. **Fig. 4** shows that with the 0.5-degree angle taper, both center and transition regions have high stress concentrations. **Fig. 4** shows the 1-degree angle taper that has the desirable stress pattern; the high stress region is located at the center of the specimen. The variation in stress in the gauge length is also very low, ranging from 75 (dark blue) to 80 (bright red), which is only 5 %. This indicates a very even stress distribution.

The fluid dynamics of the concrete and mold may produce inconsistent effective dosages in the gauge length and encourage alignment of fiber parallel to the axis of load application [1]. This test, however, determines the load per fiber and does not correlate the result of a particular dosage rate. Separate testing

FIG. 2
DTT specimen configuration.

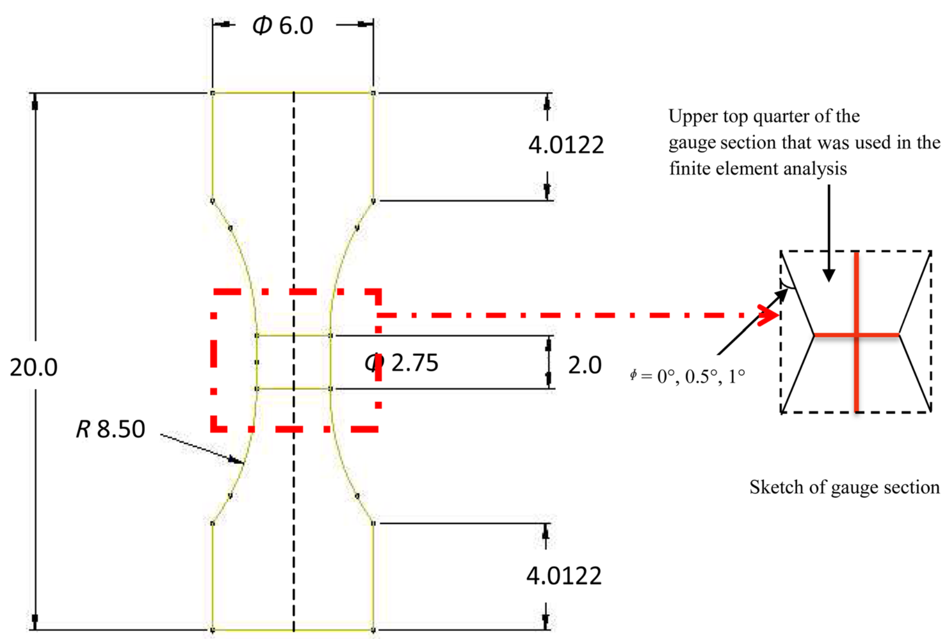
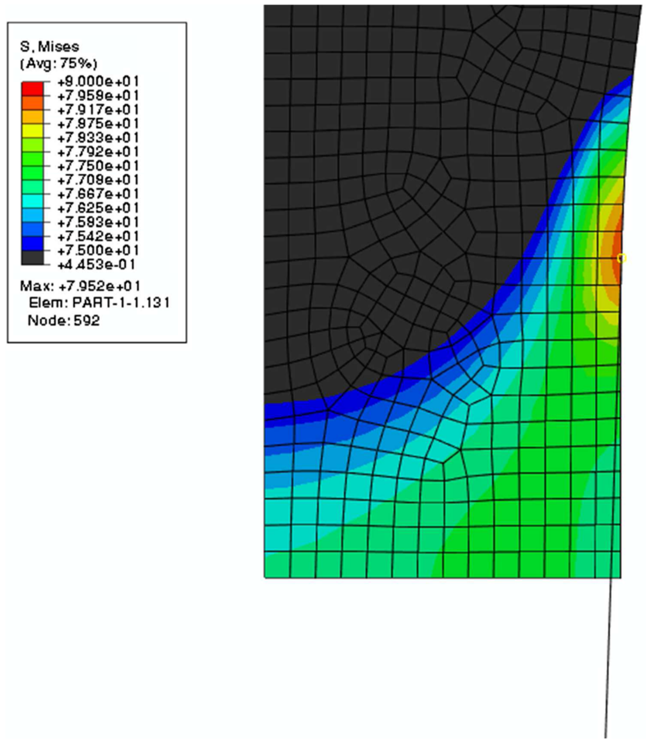


FIG. 3

The effect of the taper angle—upper top quarter of the gauge section without taper angle.



must be conducted to determine the number of parts per unit area and the associated variation. This addresses one of the biggest issues with testing of fiber concrete—high variation of results. Most of this variation comes from the distribution of fibers. Specimen preparation can play a big role in this. Testing of parts per area as a function of dosage is inexpensive and can be done on multiple samples or larger sections to get statistically significant results.

Specimen Preparation

The specimen preparation shall be conducted at room temperature in accordance with ASTM E111, with the following modifications:

1. Specimens shall be molded in non-absorptive mold with the use of a form release agent. The mold shall produce specimens similar to **Fig. 2**.
2. The addition of fiber shall comply with the manufacturer's installation instructions.
3. Placement of the concrete into the mold shall occur in three stages with vibration for each stage.
4. Specimens shall remain in the molds for a period of 24 h after casting and then cured in accordance with ASTM 192 [12].
5. The minimum diameter of the coupon is set to be at least twice the length of the pieces of twisted steel micro rebar being tested.

Test Preparation

Prior to testing, standard adhesive concrete anchor size (1/2 in. diameter) is installed at both ends of the specimen and embedded a minimum of 89 mm (3.5 in.) into the sample in accordance with anchor manufacturer's installation instructions. Samples are fixed in the testing machine with a universal joint on one end jaw on the other end capable of developing the expected tensile force. Three displacement-measuring devices linear variable differential transformers (LVDTs) (with a resolution of 0.1 μm and an accuracy of 1 μm shall be attached to the specimens to record the actual displacement. The LVDTs shall be centered about the middle of the gauge length of the tension specimen (**Fig. 1**).

A minimum of three replicate specimens of each configuration dosage and mix design are required.

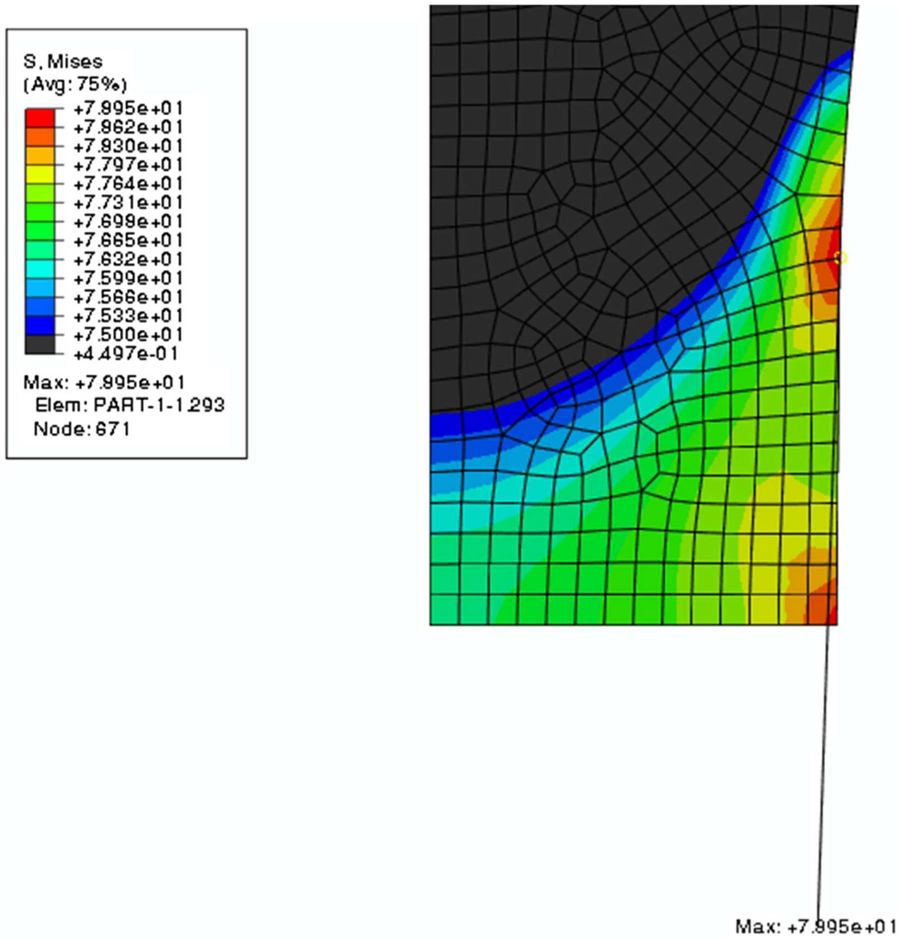
Machine Specifications

A universal tension tester capable of operating under the following parameters is required:

- The machine shall be capable of a sampling rate of 0.1 Hz minimum.
- The machine shall be capable of 0.005 in./min (0.0127 mm/min) co-axial movement rate.
- The machine shall be able to deflect at least 0.25 in. (6.4 mm).

FIG. 4

The effect of the taper angle—upper top quarter of the gauge section with 0.5 degree taper angles.



- The machine shall be capable of containing the coupon shown in **Fig. 2**.

Test Procedure

The specimen is loaded to obtain data to plot loading, load-deflection curve at a specified crack width of 1 mm (0.004 in.) (**Fig. 6**).

Reporting Specifications and Results

The reporting requirements listed in ASTM E111 Sections 10.8 and 10.1.9 shall be replaced with the following reporting requirements.

- The tensile load deflection curve.
- After the specimen is broken, the diameter at break, the total number of steel fiber on both faces of the broken section extending out of the broken plane at least 0.04 in. (1.00 mm) and at 30 degrees or greater.
- The tensile load at the strain limit (measured from 0–1 mm displacement) shall be determined. The associated strain values shall be computed based on the section size and gauge length.
- Concrete compressive strength tests (ASTM C39/C39M) [13]. Three cylinders shall be tested for each unique mix design within 24 h of tensile testing in accordance with Section 5.66. The average cylinder test results shall be reduced to the specified compressive strength in accordance with ACI 318 Section 5.3.2.2 [14].

The Use of the New Direct Tension Test Results

EXPERIMENTAL RESULTS OF TSMR

Multiple DTTs were conducted [10,15] using direct tension testing of TSMR in a concrete matrix and initiated at the ISO accredited element laboratory [16] (**Fig. 7**). Twenty-four distinct dosage levels of TSMR were tested as well as several baseline samples with no TSMR and various concrete compressive strengths were used. **Table 2** shows the data collected including the tensile force at 1 mm displacement the associated strain, the diameter at the break, number of TSMR above 30-degree angle

FIG. 5

The effect of the taper angle—upper top quarter of the gauge section with 1.0 degree taper angles.

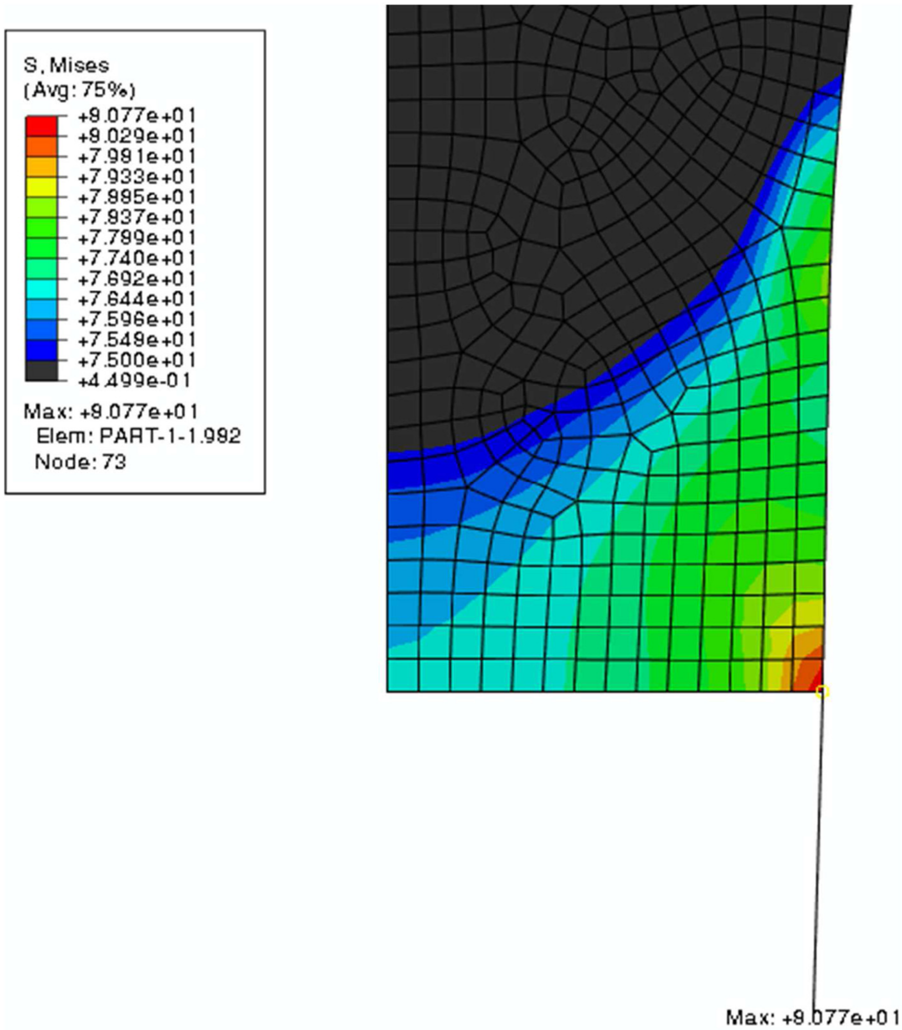


FIG. 6

Idealized direct tension-load deflection curve.

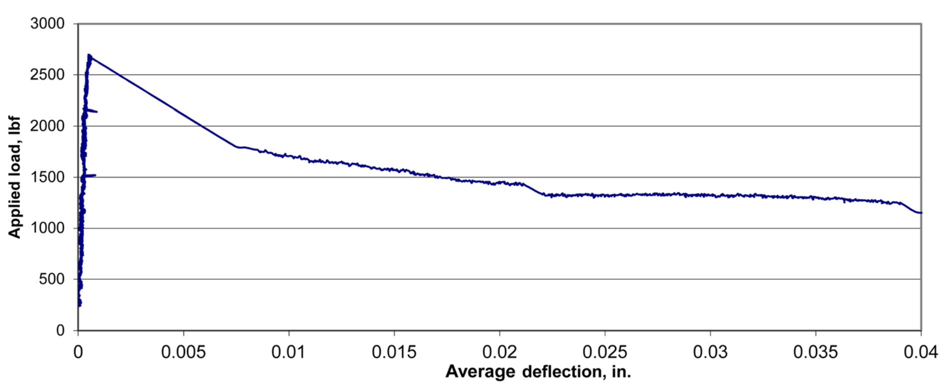
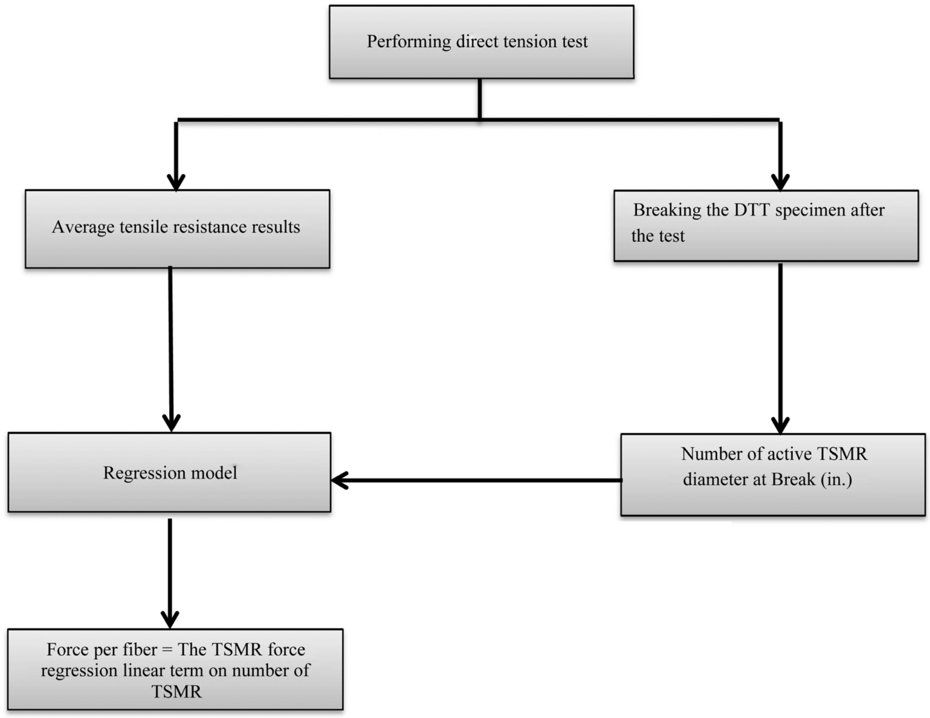


FIG. 7
Flow chart showing the use of the new direct tension test results.



per in.^{2} and the concrete compressive strength. To determine the significant predictors, statistical analyses are required.

FIBER INCLINATION ANGLE

Tests have shown that inclination angle so long as the angle is greater than 30 degrees does not have a significant effect on TSMR load-carrying capacity [17]. The increase in bearing stress (normal force, Q in **Fig. 8**) combined with the twisted geometry increases the bond offsetting the decrease in force transmission across the plain of peak stress (crack) because of the angle (from vector mechanics). The independence of inclination angle allows simple summation to be used to determine the total force as a function of the number of TSMR with inclination angles greater than 30 degrees counted in the test specimen. The lack of correlation between angle and pullout force is verified experimentally.

TABLE 1 Results of Monte Carlo simulation runs for part orientation.

Run	Result
1	0.887254902
2	0.886754702
3	0.890556222
4	0.881752701
5	0.892857143
6	0.897458984
Average	0.889439109

A standard two-sided t-test of the data shown in **Fig. 8** is employed to evaluate the effect of inclination angle. The test statistic, p-value, is 0.87 for the angle variable and 7×10^{-13} for the constant. This proves the hypothesis is correct; the inclination angle does not have a significant effect on pullout force.

In addition, Monte Carlo simulation was used to determine the percentage of TSMR at least 30 degrees relative to the tensile load [18]. Ten thousand (10,000) random helix orientations were generated and the average number meeting the criteria were recorded for each run. The average value was computed from six runs of 10,000 orientations each. The result indicates 88 % of all TSMR are oriented with angles greater than 30 degrees. The results are summarized in **Table 1**.

These data in **Table 2** were analyzed using a regression model and the two significant predictors were determined to be the number of fibers and the concrete compressive strength ($f'c$). **Fig. 9** shows a contour plot using load at 1 mm crack width, TSMR per square inch, and $f'c$.

In general, the higher the R^2, the better the model fits the data. The R^2 value is a statistical measure of how closely the data fit the regression line. The TSMR model has an R^2 of 0.84.

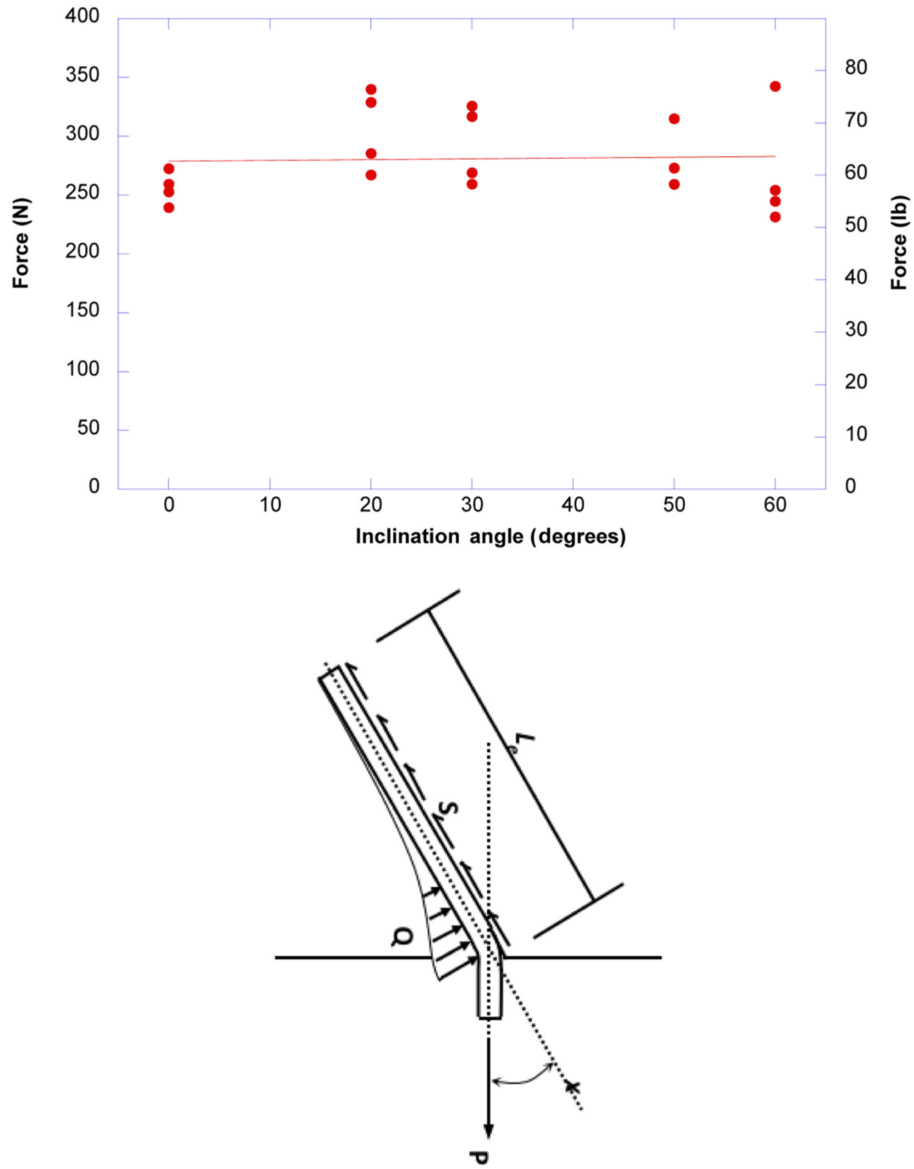
The regression model best-fit equation can be obtained from **Fig. 9**. This regression fit is given by Eq 1 (**Fig. 10**):

$$\text{Load at } 1\,\text{mm}\,(0.040\,\text{in.})\ \text{Displacement} \\ = X + (Y \times \text{Number of TSMR}) + (Z\ xf'c)\,\text{lb}$$

The coefficient of variation (COV) is calculated using the standard deviation for each of the components of the regression

FIG. 8

Inclination angle and angle of inclination versus peak pullout load.



equation. The linear equation consists of three parts, The TSMR force regression model intercept constant (X), the TSMR force regression linear term on number of TSMR (Y) and the TSMR force regression concrete compressive linear term (Z). For TSMR, the X constant (-121.1), the Y linear term (22.82), and the $f'c$ linear term (0.025). These coefficients represent the average values for a specific TSMR, and may be different for various TSMR. This potential difference is represented by a standard deviation for the three terms. In those tests for TSMR, the COV is 0.0096 (**Table 2**).

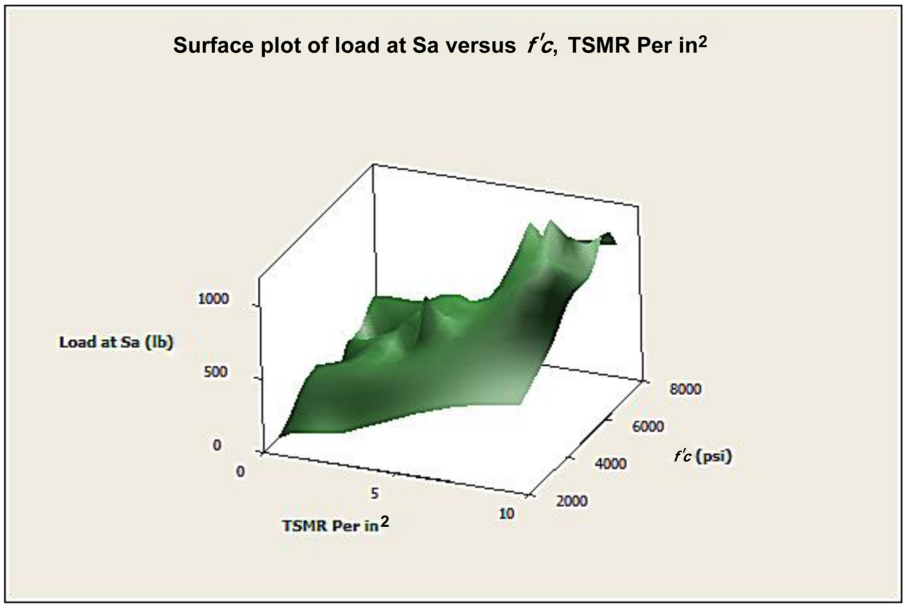
Discussion

Flexural test is the dominant method used to determine the tension response of steel fibers. These flexural tests are performed by applying three- or four-point loads on a beam [5–7]. There are many concerns with beam tests involving a high COV for a single operator, on average 20 % [5,6], and test results could vary significantly depending on specimen size, concrete casting method, and support devices used [19]. In addition, the beam support points need to be able to rotate to accommodate the post crack deflected rotation of the beam. If the supports do not rotate easily, friction builds up creating a force that resists the downward load. The result is increased load capacity. Different frictional capacities of the fixtures between laboratories create variability. It has been shown that free rolling supports can provide 30 % less capacity compared to fixed supports.

Regarding the test results, tensile resistance is then derived by assuming a relationship between the residual flexural stress (which only exists in linear elastic materials and is invalid after

FIG. 9

Actual data plot of TSMR per square inch, concrete compressive strength, and load at Sa.



a crack forms) and direct tensile stress [8]. A multiplier of 0.37 and 0.45 (which assumes linearly decreasing load as crack width increases) is typically used to relate the flexural stress in beams with large cracks (3.5 mm) to direct tensile strength [9]. Beam testing is also plagued with so-called "size effect," the non-scalability of results to larger or smaller sections and/or cross correlation of crack size, fiber length, and specimen size on the results [9].

On the other hand, the proposed DTT method was developed to directly and accurately capture the direct tensile response of steel-fiber-reinforced concrete. The proposed test method consists of three-dimensional "hourglass"-shaped specimen under uniaxial tensile loading using the universal tension tester machine. The test uses standard adhesive concrete anchors installed at both ends of the specimen, which are fixed in a testing machine with a universal joint on one end and a jaw at the other end. This machine must be capable of developing the expected tensile force and the device eliminates any variation of the test procedure that results from using a fixture as with the flexural beam test. The proposed direct tension test

FIG. 10

Regression fit for data shown in **Fig. 9**.

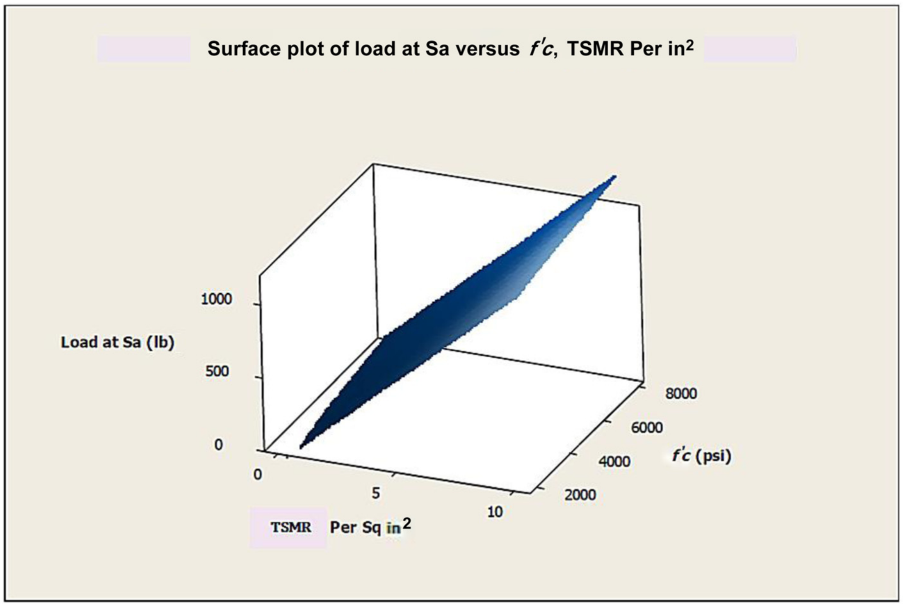


TABLE 2 Test results used in regression analysis.

Sample	Number TSMR Above 30 Degrees	Diameter at Break (in.)	TSMR (#TSMR Above 30/Area of Section) per in.^{2}	$f'c$ (psi)	Load at 1 mm Displacement (lb)	Strain
1	0	2.735	0.0	5900	0	0.014 %
2	0	2.723	0.0	5900	0	0.016 %
3	0	2.717	0.0	5900	0	0.011 %
4	4	2.76	0.7	6980	0	0.024 %
5	7	2.778	1.2	7020	213	0.021 %
6	19	2.725	3.3	7020	706	0.025 %
7	19	2.683	3.4	7020	440	0.025 %
8	52	2.835	8.2	5680	984	0.022 %
9	14	2.779	2.3	5680	155	0.018 %
10	13	2.712	2.3	5680	251	0.019 %
11	9	2.712	1.6	7960	311	0.021 %
12	34	2.686	6.0	7960	989	0.032 %
13	25	2.821	4.0	7960	326	0.023 %
14	17	2.81	2.7	7090	479	0.018 %
15	12	2.845	1.9	7090	324	0.018 %
16	18	2.755	3.0	7090	404	0.024 %
17	20	2.735	3.4	6130	688	0.016 %
18	15	2.705	2.6	6130	180	0.016 %
19	46	2.755	7.7	6130	1046	0.018 %
20	19	2.734	3.2	6880	272	0.024 %
21	43	2.725	7.4	7270	1168	0.019 %
22	36	2.75	6.1	7270	821	0.014 %
23	26	2.74	4.4	7270	418	0.013 %
24	53	2.708	9.2	7390	1102	0.031 %
25	0	2.823	0.0	2750	0	0.017 %
26	0	2.734	0.0	2960	0	0.016 %
27	0	2.846	0.0	2960	0	0.017 %
28	0	2.858	0.0	2960	0	0.016 %
29	10	2.86	1.6	2950	56	0.019 %
30	9	3.002	1.3	2950	91	0.014 %
31	11	2.749	1.9	2950	97	0.015 %

requires a very slight taper of the specimen to minimize stress variation while encouraging the development of the first crack in the center of the gauge length. As a result, the laboratory test data for the direct tension test showed that single test operation with COV of 9 %.

After the direct tension test is complete and the section has cracked, the number of fibers at the cracked section are counted. This addresses one of the biggest issues with testing of fiber concrete, high variation of fiber performance results. Most of these variations come from the distribution of the fibers. The distribution of the fibers is tested independently of the tension test.

Regarding the test results, unlike the standard flexural beam tests, the direct tension test method is able to determine the uniaxial tensile response of steel fibers. The test is a practical and robust for determining the average tensile force per fiber [9]. After the data of the direct tension test and relative test of parts per area has been gathered, additional statistical analyses should be performed for the test results. This analysis produces a regression model of the fiber response in a concrete section.

Conclusion

The proposed direct tension test specimen shape and test method addresses all the issues of the current flexural beam tests. The method represents a fundamental concept for a reliable and practical method for the investigation of the direct tensile response of steel-fiber-reinforced concrete. The DTT is a robust test method with the ability to determine the uniaxial tensile response of steel fibers, and determining the tensile strength of a section as a function of fiber count rather than dosage rate allows for the formulation of a regression model in terms of force per fiber.

The proposed approach that determines the tensile force per fiber is unique because it solves the problem of variable fiber performance because of specimen size and loading geometry. This is accomplished by isolating the two primary variables of fiber performance in concrete, which are force per fiber and fiber distribution. Using this test method, the distribution variable can be tested independently of the force variable.

Separating the distribution variable allows for less expensive testing of smaller specimens without compromising accuracy.

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