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Twisted Steel Micro Reinforcement

Advantages of microscopic composites

by Luke R. Pinkerton, Joseph L. Stecher, and Jeff Novak

Reinforced concrete can be described as a "macroscopic" composite made up of a concrete matrix and steel bar reinforcement. Because the bars are large and widely distributed, they effectively carry load only after the concrete develops a macrocrack. Therefore, conventional reinforcing bars are reactive reinforcement.

A "microscopic" composite can be created by combining concrete with HELIX™ twisted steel micro reinforcement (referred to herein as micro reinforcement). Because this type of reinforcement is distributed throughout the matrix and is continuously deformed like reinforcing bars, it carries load both before and after the concrete develops a macrocrack (dominant crack). Thus, micro reinforcement is proactive reinforcement that also acts as reactive reinforcement at higher strain levels.

This article provides a description of the fracture mechanisms of micro-reinforced concrete composite, a novel method to measure performance characteristics of the composite, and a design methodology using the proactive and reactive reinforcement properties.

Functional Mechanisms

HELIX micro reinforcement is produced with a unique twisted profile (Fig. 1) that allows each piece to bond to the matrix over its full length. In addition, the reinforcement must untwist as it pulls out of the concrete. This makes this product significantly different than traditional steel fibers because pullout is governed by twisting resistance rather than friction.

Throughout this article, the described strains are based on deformation of the concrete, both before and after formation of a dominant crack. The limit of usable strain in the micro-reinforced concrete is equivalent to a strain of 0.01 (100 microstrain) in reinforcing bars. This equates to a crack opening in reinforced concrete of 0.04 in. (1 mm).

In addition, stress in the concrete is based on engineering stress (tensile load divided by a plane area of concrete under consideration). For example, the engineering stress in a test coupon is computed by dividing the total applied load by the cross-sectional area of the neck of the coupon. After a dominant crack occurs, the engineering stress is still based on the original cross-sectional area of the specimen.

The performance of a micro-reinforced concrete composite in tension is described using a multiphase approach similar to the one proposed by Aveston and Kelly[1] for concrete with traditional steel fibers. When loaded in tension, micro-reinforced concrete goes through four fundamentally different phases prior to complete fracture. Figure 2 shows the four phases as they appear on an idealized load-deflection curve of a direct tension test:

- Phase I—The concrete matrix carries the tensile load until the first microcrack forms (0 to 10 microstrain);
- Phase II—The micro reinforcement begins taking up load, allowing additional microcracking of the concrete as load is distributed among the fibers (10 to 200 microstrain);
- Phase III—Microcrack localization forces the micro reinforcement to carry the entire load and begin to elongate within the crack openings. In this phase, the engineering stress in the composite is a function of the micro reinforcement dosage (200 to 1000 microstrain); and
- Phase IV—The ends of the micro reinforcement begin to move relative to the matrix (>1000 microstrain).

Fig. 1: HELIX twisted steel micro reinforcement elements

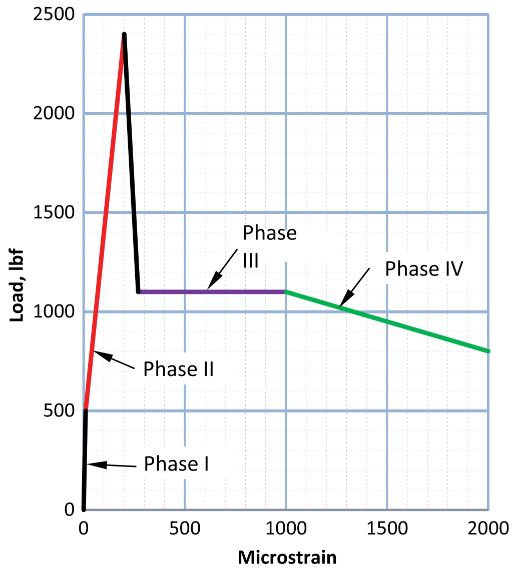

Fig. 2: Idealized direct tension-load deflection curve (Note: 1 lbf = 0.004 kN)

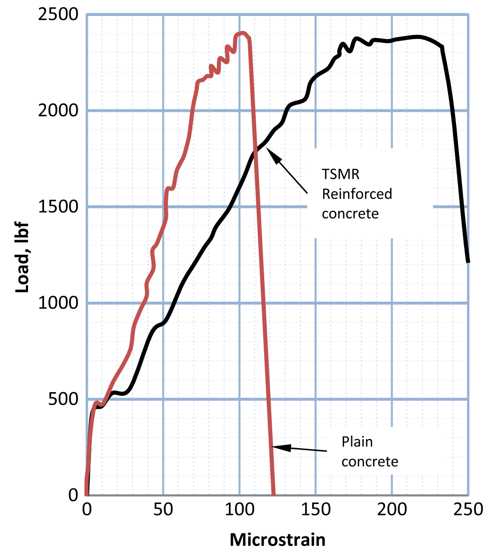

Fig. 3: Phases I and II for plain and micro-reinforced concrete (Note: 1 lbf = 0.004 kN)

Comparing plain and micro-reinforced concrete (Fig. 3), we find that both materials are quite stiff in Phase I until microcracking initiates at about 10 microstrain. Tests show that this corresponds to a tensile stress of about 50 psi (0.34 MPa). In plain concrete, Phase II ends with micro-crack localization and failure at about 100 microstrain. But in micro-reinforced concrete, the load is redistributed across the microcracks. As the stress increases above 50 psi (0.34 MPa), the redistribution of load to the micro reinforcement results in a slight softening, allowing the composite to resist well over 200 microstrain before formation of a dominant crack. Analysis of direct tension tests has shown that this increase in strain capacity is statistically significant, with a confidence level of over 99%.

In Phase III (Fig. 2), it's important to note that the micro reinforcement begins to stretch but does not pull out of the matrix. Pullout begins in Phase IV. As strain increases during the final phase, the composite softens incrementally as individual micro reinforcement pieces pull out of the matrix as they untwist.

Performance Characterization

Tensile resistance is the primary engineering parameter needed for design with micro-reinforced concrete. While beam tests have been the traditional way to evaluate fiber-reinforced concrete, stresses must be calculated using the section properties for the uncracked section. Because the fiber stresses vary over the depth of the specimen (both before and after cracking), the flexural test doesn't adequately measure the performance of micro-reinforced concrete. We therefore apply direct tension tests to evaluate micro-reinforced concrete using a load frame and a cylindrical tensile test specimen, as shown in Fig. 4.

The reduced gauge section of the test specimen has large fillet radii to minimize stress concentrations and encourage the development of a dominant crack in the center of the gauge length. Load is applied through adhesive anchors embedded in the grip zone of the test coupon. Strain is monitored using a strain gauge with a 4 in. (100 mm) gauge length. The specimen is pulled under displacement control until it reaches an engineering strain of 2% (2000 microstrain).

The test setup and instrumentation are capable of accurately measuring strain before and after the formation of a dominant crack. The data collected in the direct tension test is a load-deflection plot similar to what is shown in Fig. 2. After fracture, the number of micro reinforcement crossing the failure plane is counted, and the load determined. As discussed in the following section, the results of this test are not related to a particular dosage rate—only the load per micro reinforcement element.

During production of specimens, micro reinforcement within the gauge length tends to align parallel to the axis of the specimen and the direction of applied load. Inspection of broken specimens and geometric analyses using Monte Carlo simulations indicate that 88% of the micro reinforcement elements crossing the dominant crack are at inclination angles greater than 30 degrees to the crack surface. It has also been shown that micro reinforcement elements with inclination angles of at least 30 degrees will pull out of the concrete rather than fracture. Thus, the total force applied to the test coupon will be proportional to the number of elements with inclination angles greater than 30 degrees crossing the dominant crack.

Because the mold for the tension specimens affects the quantity of micro reinforcement crossing the failure surface, a separate test is used to link a dosage rate of micro reinforcement to the number of pieces per square inch (square meter) of

Fig. 4: Direct tension test specimen mounted in a load frame. Load is applied to adhesive anchors embedded in the grip zones of the specimen, centered on the axis of the specimen. The strain gauge comprises four linear variable differential transformers in spring-actuated precision gauge heads. Tests are conducted in accordance with ASTM E111, "Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus"

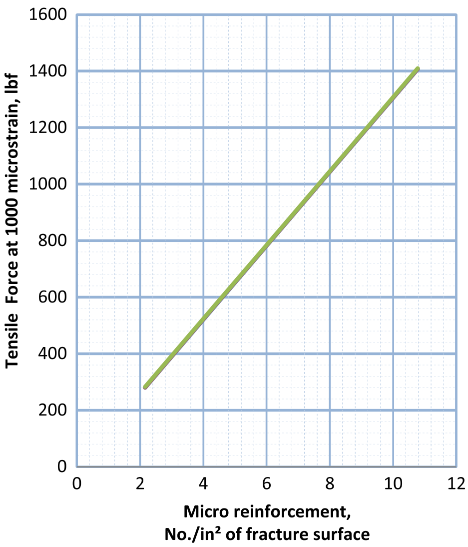

Fig. 5: Example best-fit relationship for tensile force (at a strain of 1000 microstrain) as a function of micro reinforcement crossing the fracture surface at angles of 30 degrees or more. This example is for concrete mixtures with 4000 psi (27.6 MPa) compressive strength (Note: 1 lbf = 0.004 kN; 1 in.^{2} = 0.0006 m^2)

fracture area in a more generic section. This is accomplished by counting the micro reinforcement crossing the failure plane for a beam specimen produced and tested according to ASTM C78/C78M, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)."

Using mixtures with a range of micro reinforcement dosages, we have developed relationships for total tension load (strains up to 1000 microstrain) as a function of the compressive strength of the concrete and the number of micro reinforcement elements crossing the dominant crack surface at angles of 30 degrees or more. Figure 5 shows the tensile force as a function of elements crossing the fracture surface for a 4000 psi (27.6 MPa) mixture.

Proactive and Reactive Reinforcement

We previously defined proactive reinforcement as reinforcement that begins taking load prior to the formation of a dominant crack. Common examples of proactive reinforcement include the glass or carbon fibers in fiber-reinforced polymers. In these composite materials, the fibers dominate the physical properties. In contrast, the reinforcing bars in traditional reinforced concrete provide only reactive reinforcement—they have no significant effect on the properties of the composite of concrete and steel prior to the development of a crack.

The unique geometry of micro reinforcement provides superior bond, allowing it to act as proactive reinforcement (Phases I and II in Fig. 2 and 3). With increasing dosages, the modulus of rupture increases (Fig. 6). While this increase is not considered in design, the stable post-cracking behavior of micro-reinforced concrete (Phase III in Fig. 2) mimics the stable tensile response of reinforcing bars in concrete, allowing use of standard design equations typically applied for reinforced concrete and greatly simplifying the design approach.

Design

While micro reinforcement offers unique advantages due to its ability to provide proactive response, it is designed using the same cracked section assumptions as for standard reactive reinforcement.

Micro reinforcement design is accomplished with four simple steps:

- Computation of the area of steel reinforcing required for temperature and shrinkage reinforcement or flexural reinforcement;
- Selection of the micro reinforcement design class;
- Determination of the required number of micro reinforcement; and
- Calculation of micro reinforcement dosage per unit volume of concrete.

The micro reinforcement contribution to the tensile behavior of the concrete (characterized by the previously described testing) is applied as a rectangular stress block in the tensile zone of the concrete section. The first step requires that the engineer uses standard design equations to compute the nominal area of steel required at the centroid of the tensile region.

The classes for micro reinforcement design are based on the support and geometric conditions of the application. Soil-supported structures, requiring only temperature and shrinkage reinforcement, are Class A applications. Structural concrete that is soil-supported, carries load as an arch, or is in a vertical component with closely spaced lateral supports is considered a Class B application. All other structural applications, including suspended concrete floors, are Class C applications. Class C applications require reinforcing bars to provide load redistribution capacity. The flowchart shown in Fig. 7 can be used as a guide for determining the design class for particular applications.

The micro reinforcement dosages are based on limit state design methods, with load factors consistent with standard building practice.[2,3] Dosages selected for Classes A and C have been chosen to provide concrete strengths that match the average strength values as recommended in ACI 360R[4] and required by ACI 318,[5] respectively.

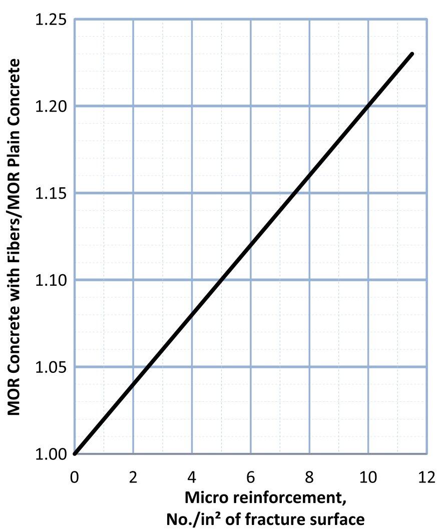

Fig. 6: Effect of micro reinforcement on modulus of rupture (ASTM C78/C78M) (Note: 1 in.^{2} = 0.0006 m^2)

Once the design class is known, the number of micro reinforcement elements required to resist the tensile load (in much the same way as one determines the quantity of reinforcing bars required in a section) is calculated. To simplify the design process, the required micro reinforcement quantities have been tabulated based on the characterization data obtained from direct tension testing (refer to the examples in Fig. 8). The required micro reinforcement dosage (weight of fibers per unit volume of concrete) is calculated based on the cross-sectional area loaded in tension (Fig. 8).

Finally, it's important to note that restrictions are imposed to minimize the risk of catastrophic failure. If support conditions do not meet the requirements of ACI 318, Chapter 22, a hybrid system (combination of Helix and reinforcing bars) is required.

Conclusions

The design method for HELIX twisted steel micro reinforcement has undergone third-party testing and validation and is now described in an evaluation report for use for temperature and shrinkage reinforcement.[6] The method has also been peer-reviewed for compliance with Section 1.4 of ACI 318[5] and Reference 7 for selection of micro reinforcement dosages for structural applications (Class B and Class C structures). The peer reviewer has also studied over 100 design cases in which either laboratory or field testing was conducted, dating back 10 years, to confirm the design method produces designs with strengths that meet or exceed predicted values. Additional data and documentation are available for review.[8]

The micro reinforcement can be blended into standard structural concrete mixtures and used alone or in conjunction with conventional reinforcing bars.

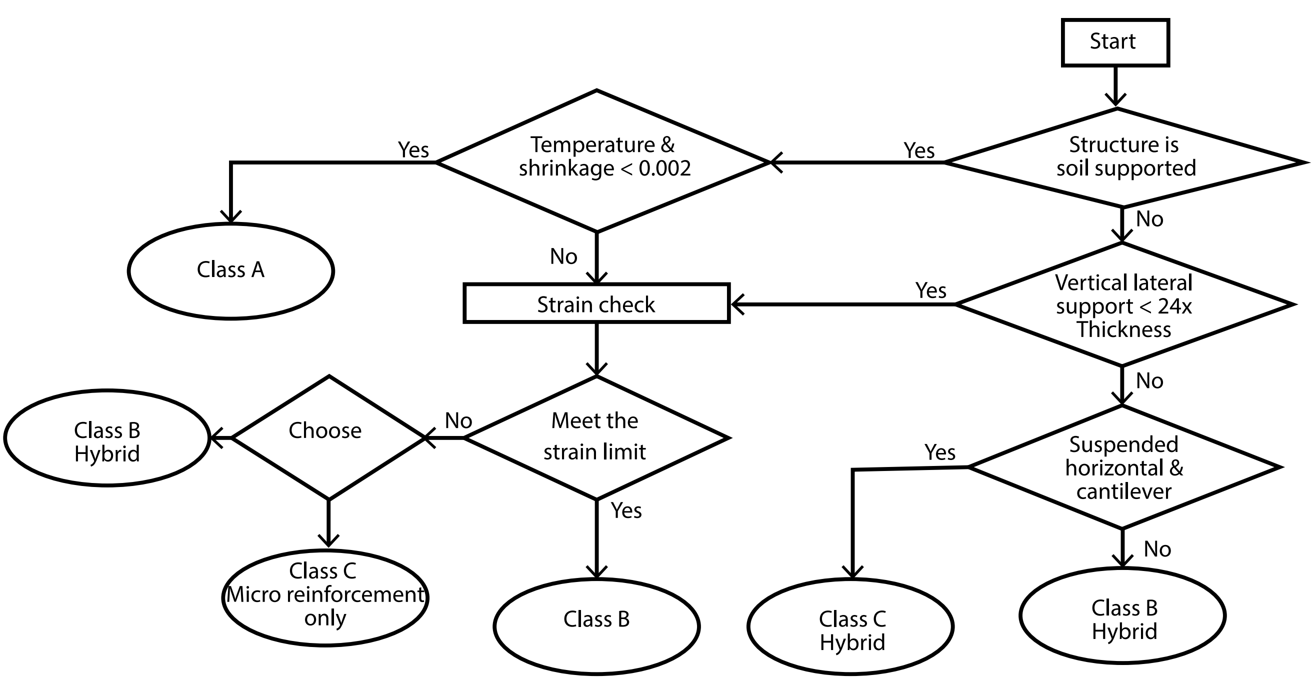

Fig. 7: Design flowchart, showing the classification of applications for micro reinforcement composites

(a)

Table 1: Helix Micro-rebar Replacement

Fy = 60 ksi Nominal area of steel in tension As (in²/ft)	Nominal number of Helix Micro Rebar required - Imperial			Fy = 500 Mpa Nominal area of steel in tension As (mm²/m)	Nominal number of Helix Micro Rebar required - Metric		
	3000 psi	4000 psi	5000 psi		20 Mpa	30 Mpa	40 Mpa
0.028	37.8	37.3	36.7	28	70.0	69.2	68.4
0.040	53.6	53.1	52.5	45	111.9	111.1	110.3
0.050	66.8	66.2	65.7	50	124.2	123.4	122.6
0.060	79.9	79.4	78.8	79	195.6	194.8	194.0
0.080	106.2	105.7	105.1	89	220.3	219.5	218.7
0.090	119.4	118.8	118.3	90	222.7	221.9	221.1
0.100	132.5	132.0	131.4	100	247.3	246.6	245.8
0.110	145.7	145.1	144.6	111	274.4	273.6	272.9
0.120	158.8	158.3	157.7	113	279.4	278.6	277.8
0.150	198.2	197.7	197.2	141	348.3	347.5	346.7
0.160	211.4	210.9	210.3	150	370.5	369.7	368.9
0.170	224.5	224.0	223.5	154	380.3	379.5	378.8
0.180	237.7	237.1	236.6	179	441.9	441.1	440.3
0.200	264.0	263.4	262.9	200	493.6	492.8	492.0

(b)

Table 2: Helix Micro-Rebar Dosage Rate

Number of Helix per unit area in tension (Helix/in²)	Helix dosage rate, Hd (lb/yd³)			Number of Helix per unit area in tension (Helix/m²)	Helix dosage rate, H_d (kg/m3)		
	3000 psi	4000 psi	5000 psi		20 Mpa	30 Mpa	40 Mpa
1.18	9.0	9.0	9.0	2000	5.0	5.0	5.0
1.25	9.0	9.0	9.0	2500	5.0	5.0	5.0
1.43	9.0	9.0	9.0	3000	5.3	5.3	5.3
1.50	9.0	9.0	9.0	3500	6.2	6.2	6.2
1.53	9.0	9.0	9.0	4000	7.1	7.1	7.1
1.75	9.0	9.0	9.0	4500	8.0	8.0	8.0
2.00	9.3	9.3	9.3	5000	8.9	8.9	8.9
2.25	10.4	10.4	10.4	5500	9.8	9.8	9.8
2.50	11.6	11.6	11.6	6000	10.6	10.6	10.6
2.75	12.8	12.8	12.8	6500	11.5	11.5	11.5
3.00	13.9	13.9	13.9	7000	12.4	12.4	12.4
3.25	15.1	15.1	15.1	7500	13.3	13.3	13.3

Fig. 8: Portions of design tables used to determine required dosage of micro reinforcement: (a) the total number of micro reinforcement required to replace a given area of conventional reinforcing bars varies with concrete strength and design class; and (b) the micro reinforcement dosage is based on the required number of micro reinforcement per unit area. The method and models that serve as its basis have been validated with third-party testing,[6] full-scale field testing, and peer reviews by structural engineers

Since 2003, when HELIX micro reinforcement came to market, it has been used on various concrete projects including structural foundations, structural footings, slabs (slab-on-ground, slab on metal deck, elevated), walls (cast-in-place, tilt-up, precast), pavements/toppings, bridges, precast applications, and tornado/hurricane and blast-resistant structures. For more information on individual projects, visit **www.helixsteel.com/projects**.

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Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

Selected for reader interest by the editors.

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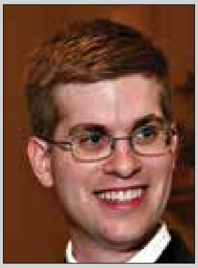

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