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EVALUATION CRITERIA FOR TWISTED STEEL MICRO-REBAR (TSMR) IN CONCRETE

EC 015 – 2016
(Adopted - November 2013, Revised – January 2016)

1.0 INTRODUCTION

1.1 **Purpose:** The purpose of this evaluation criteria is to establish requirements for Twisted Steel Micro Rebar (TSMR) in an independently reviewed evaluation report under the 2015, 2012 and 2009 *International Building Code*® (IBC) and the 2015, 2012 and 2009 *International Residential Code*® (IRC). Bases of recognition are IBC Section 104.11 and IRC Section R104.11.

1.2 **Scope:** This evaluation criteria applies to Twisted Steel Micro Rebar (TSMR) used as an alternative reinforcement to materials and methods specified for structural concrete designed and constructed in accordance with ACI 318 and for structural slabs on grade designed and constructed in accordance with ACI 360.

2.0 REFERENCED STANDARDS

2.1 **General:** Referenced standards shall be applied consistent with the provisions of the applicable edition of the IBC and as noted herein.

American Concrete Institute

ACI 224.2-92 (2004)	Cracking of Concrete Members in Direct Tension
ACI 318-14	Building Code Requirements for Structural Concrete
ACI 318-11	Building Code Requirements for Structural Concrete
ACI 318-08	Building Code Requirements for Structural Concrete
ACI 360R-10	Guide to Design of Slabs-on-Ground

ASTM International

ASTM C39-14a	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
ASTM C78-10e1	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
ASTM C94-14	Standard Specification for Ready-Mixed Concrete
ASTM C192-07	Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
ASTM C330-14	Standard Specification for Lightweight Aggregates for Structural Concrete
ASTM C494-13	Standard Specification for Chemical Admixtures for Concrete

ASTM C1609-12	Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)
ASTM E111-04 (2010)	Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
ASTM E119-2012A	Standard Test Methods for Fire Tests of Building Construction and Materials

Canada Standards Association

CSA A23.2-16C	Standard Test Method for Determination of Steel or Synthetic Fibre Content in Plastic Concrete

International Code Council

2015, 2012 and 2009 IBC	International Building Code®
2015, 2012 and 2009 IRC	International Residential Code®
AC208	Acceptance Criteria for Steel Fibers in Concrete

International Organization for Standardization

ISO/IEC 17011:2004	Conformity Assessment--General Requirements for Accreditation Bodies Accrediting Conformity Assessment Bodies
ISO/IEC 17025:2005	General Requirements for the Competence of Testing and Calibration Laboratories

Japan Society of Civil Engineers

JSCE SF-4(1984)	Method of Test for Flexural Strength and Flexural Toughness of Steel Fiber Reinforced Concrete, Japan Society of Civil Engineers

Underwriters Laboratories

UL 263-11	Standard for Fire Tests of Building Construction and Materials

3.0 DEFINITIONS

3.1 General. Where the following terms appear in this Evaluation Criteria, such terms shall have the meaning as defined in this section.

Hybrid Design: A design that includes a combination of both deformed reinforcing bars and TSMR.

TSMR Design Classes: There are four TSMR design classes. The registered design professional shall select the appropriate design class based on the definitions below.

Class A – Temperature and Shrinkage Reinforcement: As a replacement for reinforcing bars or welded wire reinforcement in any application as an alternative to minimum reinforcement for the shrinkage and temperature reinforcement specified in Section 24.4 of ACI 318-14 (Section 7.12 of ACI 318-11 and -08) in members complying with the requirements of Section 14.1.3 (a or b) of ACI 318-14 (Section 22.2.1 (a or b) of ACI 318-11 and -08). This application includes replacement for temperature and shrinkage reinforcement in composite steel deck applications specified in ANSI/SDI-C1.0 or ASCE 3 and other structural plain concrete structures designed according to ACI 318-14 Chapter 14 (ACI 318-11 and -08 Chapter 22). The TSMR shall not be used to replace any joints specified in ACI 318-14 Section 14.3.4 (ACI 318-11 and -08 Section 22.3).

Class B - **Minimum Structural Reinforcement.** As a replacement for structural reinforcement in soil-supported structures including footings; structural concrete slabs supported directly on the ground (designed in accordance with ACI 318 or ACI 360 Section 11.3.3, Elastic Method); foundations; replacement for structural reinforcement in members in which arch action provides compression in the cross-section; replacement of reinforcement in pile-supported slabs on ground with un-occupied space below not to exceed the slab thickness (so failure will not result in structural collapse endangering occupants) and designed in accordance with ACI 318; and as replacement for reinforcement in structural walls in accordance with ACI 318 Chapter 14 and observing the following criteria:

- Thickness of bearing walls shall be not less than 1/24 the unsupported height or length, whichever is shorter, nor less than 5½ inches (140 mm).
- Walls shall be braced against lateral translation (walls shall be laterally supported in such a manner as to prohibit relative lateral displacement at top and bottom or on both sides of individual wall elements, such as occurs with free-standing walls or walls in large structures where significant roof diaphragm deflections).
- Under the IBC, at least one No. 5 (16 mm) reinforcing bar shall be provided around all window, door, and similar sized openings. Under the IRC, at least one No. 4 (12.7 mm) reinforcing bar shall be provided around all window, door, and similar sized openings. The reinforcing bars shall be anchored to develop f_y in tension at the corners of openings.

Class C - **Structural Concrete:** As reinforcement for all other structural concrete including in unsupported horizontal spans.

Class Cs – **Non-Linear Slab Design:** As reinforcement in structural slabs on ground designed in accordance with ACI 360 Chapter 11.3.3 Methods 2 (Yield Line Analysis) and 4 (Nonlinear Finite Element Analysis).

Twisted Steel Micro Rebar (TSMR): A steel rod or wire, with a non-circular cross section that shall be twisted at least one time (360°) about its own axis. Used as discontinuous reinforcement, the product is typically small enough to be mixed in large numbers into the concrete before placement.

Twisted Steel Micro Rebar Design Crack Width, S_a: This is the crack width resulting from tensile stresses typically measured for structural design applications. S_a represents the average upper limit of displacement in a direct tension test where the stress remains stable. S_a is set forth in Eq.-1:

$$S_a = \delta + X/3 \qquad \text{(Eq.-1)}$$

Where:
δ = material elongation as stated on raw material certification test reports, inch (mm).
X = elongation from twist, representing the materials approximate ability to "stretch" and need not be exactly determined, inch (mm).

$$X = 1 - \cos\left(\operatorname{atan}\left(\frac{n2\pi d}{l}\right)\right) \qquad \text{(Eq.-2)}^{i}$$

Where:
n = number of full revolutions of the part
d = equivalent diameter of the wire, inches (mm)
L = length of the part, inches (mm)
X = percentage reduction in length from twisting the part

The resulting values of S_a are used as a reference point for computing tensile resistance and compute maximum allowable crack width. In general the larger the S_a selected, the smaller the tensile resistance and the larger the maximum allowable crack width. S_a shall not exceed 1.0 mm (0.04 inch).

4.0 BASIC INFORMATION

4.1 **General:** The following requirements shall be considered in the evaluation of the TSMR:

4.2 **Product Description:** The following information on the TSMR as defined in Section 3.1 of this criteria shall be submitted for inclusion in the evaluation report.

a. **Raw Material Tensile Strength:** The tensile strength for raw material shall be submitted based on certification or mill tests supplied by the manufacturer.
b. **Description of Shape:** The cross sectional shape shall be described and shall be non-circular (has at least one flat edge).
c. **Cross Sectional Area:** The cross-sectional area shall be reported and computed from the cross-sectional dimensions on the raw material certification or mill tests.
d. **Minimum Twist:** The TSMR twist shall be reported and there shall be at least one 360-degree twist over the length of the product.

4.3 **Fire Resistance:** At least one roof and one floor concrete assembly designed to be reinforced with TSMR shall be tested for fire resistance in accordance with ASTM E119 or UL 263. Full-scale fire resistance testing specific to the application is not required where an accompanying engineering study prepared by a testing laboratory establishes the equivalency of the TSMR to reinforcing bars in terms of fire resistance.

4.4 **Installation Instructions:** The manufacturer shall provide the evaluation service agency and the laboratories conducting the testing a copy of its installation instructions. All test specimens, shall be prepared in accordance with installation instructions and procedures used in the field.

4.5 **Packaging and Identification:** Method(s) of packaging and product identification shall be included in the evaluation report. Identification shall include the manufacturer's name and address, product name, and the evaluation service agency's evaluation report number.

4.6 **Testing Laboratories:** Testing laboratories shall be accredited for the applicable testing procedures in accordance with ISO/IEC 17025 by a recognized accreditation body conforming to ISO/IEC 17011. Testing at a non-accredited laboratory shall be permitted by the evaluation service agency, provided the testing is conducted under the supervision of an accredited laboratory and the supervising laboratory issues the test report.

4.7 **Test Reports:** Test reports shall comply with Annex A of this criteria.

4.8 **Product Sampling:** Sampling of the TSMR for tests under this criteria shall comply with Annex A of this criteria.

5.0 TESTING AND PERFORMANCE REQUIREMENTS

5.1 **TSMR Material** - The testing laboratory shall examine TSMR specimens and verify information in Section 4.2 of this criteria.

5.2 **Basic Performance:** The TSMR shall comply with AC208 at the minimum allowable dosage.

5.3 **Tension Strength Specimens:** Tension strength tests shall be conducted in accordance with Section 6.1 of this criteria. As a minimum, the testing shall encompass the following:

5.3.1 **TSMR:** Each size of TSMR shall be tested.

5.3.2 **Concrete Proportions:** Each concrete mix design specified by the manufacturer, characterized by compressive strength and aggregate size, shall be tested. For structural lightweight concrete, aggregate shall comply with ASTM C 330, size designation 1 inch (25.0 mm) to 0.187 inch (4.75 mm).

5.3.3 **Dosage Rates:** For each concrete mix design, a range of TSMR dosage rates shall be tested. The minimum and maximum dosage rates shall be tested along with at least one intermediate dosage.

5.4 **Data Analysis:** The tensile test results shall be analyzed in accordance with Section 7.0 of this criteria.

5.5 **Performance Requirements:** The tensile test results shall comply with requirements in Section 8.0 of this criteria.

5.6 **Concrete Compressive Strength:** Compressive strength specimens for each concrete mix design containing the TSMR shall be cast, cured, and tested in accordance with applicable sections of ASTM C192 and C39 respectively.

6.0 TEST METHODS

6.1 **Direct Tensile Test:** Testing shall be conducted at room temperature in accordance with ASTM E111, with the following modifications:

6.1.1 Specimens shall be molded in a non-absorptive mold with the use of a form release agent. The mold shall produce specimens similar to Figure 1 of this criteria.

6.1.2 The addition of TSMR shall comply with the published installation instructions.

6.1.3 Specimens shall remain in the molds for a period of 24 hours after casting and then cured in accordance with ASTM C 192.

6.1.4 A universal joint shall be positioned at one end of the test specimen as shown in Figure 1 of this criteria.

6.1.5 Three displacement measuring devices with a resolution of 0.1 microns and an accuracy of 1 micron shall be attached to the specimens to record actual displacement. The LVDTs shall be centered about the middle of the gage length of the tension specimen. Figure 1 of this criteria illustrates the placement of the displacement devices.

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

6.1.7 **Anchoring:** The specimen shall be anchored with a threaded rod capable of developing the expected tensile force.

6.1.8 **Test Machine:** A universal tension tester capable of operating under the following parameters is required:

6.1.8.1 Machine shall be capable of a sampling rate of 0.1 Hz minimum.

6.1.8.2 Machine shall be capable of 0.0005 in/min (0.0127 mm/min) co-axial movement rate.

6.1.8.3 Machine shall be able to deflect at least 0.25 inches (6.4 mm)

6.1.8.4 Machine shall be capable of containing the coupon shown in Figure 1 of this criteria.

6.1.9 **Reporting:** The reporting requirements listed in ASTM E111 Sections 10.1.8 and 10.1.9 shall be replaced with the following reporting requirements.

6.1.9.1 Tensile force vs. elongation curves shall be reported.

6.1.9.2 The peak tensile force shall be determined.

6.1.9.3 The tensile force and displacement immediately preceding the formation of the first dominant crack shall be determined. The associated stress and strain values shall be computed based on the section size and gage length.

6.1.9.4 The peak post-crack tensile strength shall be determined. This value is defined as the peak load after 0.01 inch (0.25 mm) vertical displacement.

6.1.9.5 The tensile force at the strain limit (defined as S_a) shall be determined.

6.1.9.6 After the specimen is broken, the total number of TSMR on both faces of the broken section extending out of the broken plane at least 0.040 inch (1.00 mm) and at 30 degrees or greater (90 degrees defined as the TSMR being perpendicular to the cracked plane) shall be summed.

6.1.10 **Concrete Compressive Strength Tests:** Three cylinders shall be tested for each unique mix design within 24 hours of tensile testing in accordance with Section 5.6 of this criteria. The actual cylinder test results shall be reduced to the specified compressive strength in accordance with ACI 318-14 Section 19.2.1 (ACI 318-11 and -08 Section 5.3.2.2).

7.0 TEST DATA ANALYSIS

7.1 From the tensile tests in Section 6.1 of this criteria, a general linear regression model shall be developed, capable of predicting the tensile strength as a function of 1) the number of TSMR present in the broken section as set forth in Section 6.1.9 of this criteria and 2) the specified compressive strength of the concrete. The following requirements apply to the regression model:

7.1.1 The linear terms, the constant, and the standard deviation of each model shall be reported.

7.1.2 However, enough tests shall be run to establish the number of TSMR linear term as a statistically significant predictor (the maximum allowable p-value of this term is 0.05 indicating 95% significance).

7.1.3 Outliers and suspicious data points may be removed using standard statistical practices. Outliers may not be removed from the test report and their removal from the regression model shall be justified in writing along with the regression analysis results.

7.1.4 The overall average number of TSMR in the tests shall not exceed the midpoint of the range of TSMR per unit area considered (the dosage may have a bias toward the upper half of the range).

8.0 PERFORMANCE REQUIREMENTS

8.1 **Strain Capacity Increase Requirement**: Tensile test results shall indicate a statistically significant increase (minimum of 95% confidence, the maximum p-value in a two sample t-test, 0.05) in tensile strain capacity compared to structural plain concrete. A minimum of six control (plain concrete) specimens shall be considered in the analysis in addition to the minimum number of TSMR samples required in Section 6.0. Since resolution of data can be an issue in measurements of small deflections, data with slope coefficient of variation (COV) greater than 2 percent as computed according to ASTM E111, Section 9.2, Equation 4 may be neglected.

8.2 **Post-Crack Tensile Stability Requirement:** Tensile tests shall indicate that the median of the load carried at S_a divided by the maximum load after 0.01 inch (0.25 mm) displacement is equal to or greater than 0.85.

9.0 QUALITY ASSURANCE - FIELD INSPECTION:

9.1 The TSMR dosage (mass per unit volume applied to the mix) shall be certified in writing by concrete supplier.

9.2 The tested concrete compressive strength shall be the greater of 3,000 psi (20 Mpa) for Class A, Class B, and Class Cs, and 4,000 psi (27 Mpa) for Class C and specified compressive strength for the design.

9.3 Compressive strength samples shall be cast, cured, and tested in accordance with applicable sections of ASTM C192 and C39 respectively.

9.4 TMSR content (dosage) verification testing, when required, shall be conducted in accordance with CSA A23.2-16C “Standard Test Method for Determination of Steel or Synthetic Fibre Content in Plastic Concrete". The average TSMR content (CSA A23.2-16C Section 9g) shall exceed specified dosage minus the specified TSMR dosage x TSMR distribution coefficient of variation (COV defined in Section 11.1.3.2 or 11.1.3.3 of this criteria). Annex B shows the step by step procedure for developing a table of limits for various TSMR dosages. TSMR content verification is not required for the following TSMR applications:

9.4.1 Class A and B applications where one of three conditions exists which guarantee stability: soil support, lateral support, or arch action as set forth in ACI 318-14 Section 14.1.3 (ACI 318-11 and -08 Section 22.2.1).

9.4.2 Applications designed with the minimum quantity of structural reinforcing bars in accordance with ACI 318.

10.0 QUALITY ASSURANCE – MANUFACTURING:

10.1 Quality documentation complying with the IAPMO UES Minimum Requirements for Listee's Quality Assurance System (ES-010) or equivalent shall be submitted.

10.2 A qualifying inspection shall be conducted at each manufacturing facility by an approved inspection agency. The approved inspection agency shall be accredited in accordance with ISO/IEC 17020 by a recognized accreditation body conforming to ISO/IEC 17011.

10.3 An annual inspection shall be conducted at each manufacturing facility by an approved inspection agency. The approved inspection agency shall be accredited in accordance with ISO/IEC 17020 by a recognized accreditation body conforming to ISO/IEC 17011.

11.0 APPLICATION

11.1 **Analytical Model**: Standard practices for computing bending moment and shear, or any other resistance value based on the tensile strength of the concrete shall be used, replacing the tensile contribution of the continuous reinforcement with the TSMR tensile force. The structural design professional shall use the following procedure to design with TSMR.

11.1.1 **Reinforcement Area:** The nominal area of steel for the application shall be computed using standard practice and ACI 318 assuming deformed continuous reinforcement is used.

11.1.1.1 For Class A structural members, the structural design professional may assume the reinforcing bars are in the center of the concrete section.

11.1.1.2 For Class B, C and Cs structural members, the structural design professional shall determine the area of steel required at the depth of the centroid of the tension region of the concrete section.

11.1.2 **Area of Steel vs. TSMR Count Table (Figure 2 of this criteria):** The evaluation report shall include a table for each class of design consisting of at least two columns: 1) area of reinforcing bars and 2) number of TSMR required to provide the yielding force equivalent to the area of reinforcing bars listed in Column 1. The structural design professional shall refer to this table to compute the number of TSMR required to provide the tensile resistance equal to a given area of reinforcing bars. The force per TSMR shall be determined using the regression model developed in Section 7.0 of this criteria. This table may have additional columns for different concrete compressive strengths. The manufacturer shall prepare the tables and the evaluation agency shall verify the following:

11.1.2.1 Class A and B Structural Members: Micro-cracks occur and the TSMR remains bonded to the concrete. The average embedded length is ½ the length of the TSMR. The tensile test measures the response when the average embedded length is only ¼ the length of the TSMR due to the formation of a dominant crack. To obtain the maximum resistance, the tensile force at S_a shall be multiplied by the ratio of the embedded lengths: L/2 divided by L/4 = 2 to obtain the force per TSMR.

11.1.2.2 Class C and Cs Structural Members: A multiple crack condition occurs with areas of localization. The average embedded length is L/4 due to the presence of a full depth crack so no adjustment is needed and S_a is used to derive the force per TSMR.

11.1.3 TSMR Count/Unit Area vs. Dosage Table (Figure 3 of this criteria): The evaluation report shall include a table for each class of design, which includes at least two columns: 1) number of TSMR per unit area 2) TSMR dosage required to provide the number of TSMR listed in column 1. Additional columns may be provided to for different compressive strengths of concrete. The structural design professional shall divide the number of TSMR required by the area of concrete in tension and use this table to determine the TSMR dosage that needs to be applied.

11.1.3.1 The percentage of TSMR active in resisting tension shall be 88.9 percent, which is the percentage of all TSMR inclined 30 degrees or more relative to the direction of the load.

11.1.3.2 The manufacturer may elect to conduct a series of tests as described in Section 6.1 of this criteria to establish the COV at various dosages and present the results to the evaluation agency.

11.1.3.3 In the absence of actual distribution data the manufacturer may elect to use distribution data available in literature[ii] (Dupont, L. Vandewalle / Cement & Concrete Composites 27 (2005) 391–398) In this case a copy of the data and regression analysis used shall be provided to the evaluation agency.

11.1.4 TSMR Count / Unit Area vs. Tensile Stress Table (Figure 4 of this criteria): The evaluation report may optionally include a third table, which relates the number of TSMR per unit area to the corresponding tensile stress. Additional columns may be provided for different concrete compressive strengths.

11.1.5 A resistance factor shall be applied the table values to address the variance in TSMR performance in Class B and C structural members only. Average responses are used for Class A and Cs structural members. The resistance factor shall be computed in accordance with Eq-3 using standard LRFD statistical methods[iii] such that the tensile strength provided by TSMR may be substituted into the design equations for continuous reinforcement. A separate table shall be prepared for each design class.

$$\varphi = e^{-0.75\beta V_r} \quad \text{(Eq-3)}$$

Where:

φ is the target resistance factor

β is the beta factor defining the acceptable probability of failure (Section 11.2 of this criteria).

V_r is combined coefficient of variation of the response model. The coefficient of variation shall be computed using appropriate statistical laws as outlined by MacGregor (MacGregor, J.G. Safety and limit states design for reinforced concrete, Can. J. Civ. Eng. 3,284 (1976)).

11.2 Resistance Factor Calibration

The prediction of bending response from direct tension response can be overly conservative in concrete because direct tension tests do not allow as much re-distribution of load as bending tests allow. The manufacturer may optionally choose calibrate the Class B and C beta values based on experience from laboratory and field-testing to correct for this offset. Calibration shall be done by comparing bending moments predicted using the TSMR tensile stress quantities applied as a rectangular stress block below the neutral axis to the peak and the average post-crack bending moments of 3 or 4 point flexural tests on simple supports – e.g., ASTM C1609, ASTM C78, JSCE SF-4, full scale bending tests, etc.).

11.2.1 The average post crack bending moment shall be computed as the average of the 1) peak moment, 2) the moment at the midpoint deflection corresponding to a single crack width equal to S_a and 3) the moment at half of this midpoint displacement). The overall average factor of safety versus the 1) peak and 2) average post crack strength shall be determined. The mid-point deflection may be determined using the following similar triangles approach. Crack width at mid-span shall be estimated in accordance with Eq-4.

$$crack\ width = 4\ x\ \frac{h \times \delta}{span} \qquad \text{(Eq-4)}$$

Where
h is the height of the beam, inches (mm)
δ is the mid-span deflection, inches (mm)
span is the unsupported distance between supports, inches (mm)
Class A and Class Cs designs are based on average values so β shall be set to zero for these design classes. No calibration is required for these classes.

11.2.2 Class B design is based on micro-cracking behavior so a minimum average factor of safety vs. peak post crack strength of 4 shall be observed with less than 1:20 over-predictions (based on β of 1.5 at peak). The β may be adjusted until this requirement is achieved.

11.2.3 Class C design is assumes localized cracking behavior so the minimum average factor of safety vs. average post crack strength of 2 shall be observed with less than 1:20 over-predictions (based on β exceeding 1.5 at average post crack). The β may be adjusted until this requirement is achieved.

11.2.4 A third party testing laboratory, or customer shall perform tests used for calibration purposes. Since the purpose of calibration is to adjust the model to estimate performance under localized conditions and actual users conduct many of these tests, testing need not be conducted at accredited facilities. The testing laboratory may be exempt from accreditation where test results are provided and a registered design professional who reviews the data and calibration computations and agrees with the submitted results.

11.3 **Performance Based Alternative:** The design criteria outlined in this section as well as the limitations in Section 12.0 of this criteria may be modified or waived if the registered design professional shows through analysis or testing conformance to the performance requirements of the application, as also allowed in ACI 318-14 Section 1.10 (ACI 318-11 and -08 Section 1.4), IRC and IBC Section 104.11, and relevant ACI code cases[iv].

12.0 LIMITATIONS

12.1 **Class Application Limits:** The permitted applications for each class are described in detail in Section 3.1 of this criteria.

12.2 **Class A and B Strain Limits:** The average tensile strain in the concrete shall not exceed the average increase in tensile strain determined through direct tension testing set forth in Section 6.1 of this criteria. The average tensile strain in may be estimated by dividing the tensile stress in the concrete by the modulus of elasticity of the concrete (Hooke's Law). If the limit is not satisfied, Class C design is required. For Class A and B Table 3 (Figure 4 of this criteria) shall be utilized to select the provided TSMR unit tensile strength. The average strain shall be calculated in accordance with Eq-5:

$$\varepsilon \cong \frac{TSMR\ tensile\ stress}{E_{ct}} \qquad \text{(Eq-5)}$$

Where:
E_{ct} is the tensile modulus of elasticity of concrete containing TSMR, estimated as $57{,}000\sqrt{f'c}$ (psi) or $4200\sqrt{f'c}$ (MPa).
ε is the average concrete tensile strain

Note: this calculation is not meant to be a predictor of crack formation but rather a predictor of the concrete's ability redistribute loads by having at least enough tensile strain capacity at the centroid of the tensile region to resist formation of a full depth dominant cracks. These types of cracks eliminate alternative load paths and the ability for the loads to re-distribute through-out the member.

The baseline tensile strain capacity shall be set at 70 micro-strain (0.00007). This value is based on equations for the direct tensile strength (first crack strength) of normal-weight concrete set forth in ACI 224.2R Equation 3.2 and E_c shall be computed from ACI 318-14 Section 19.2.2.1 (ACI 318-11 and -08 Section 8.5.1). The TSMR strain limit shall be set at one plus the percent increase determined in accordance with Section 8.1 times this baseline. While the equations provide some differences for lightweight concrete, the change is not significant enough to require re-computation of the baseline strain. The strain increases with TSMR dosage. A simple regression analysis shall be performed to establish three or more strain limits based on average increase in strain within each range versus TSMR content per unit area. The strain increase shall not exceed the 90th percentile of all data collected for the strain increase derivation in Section 8.1 of this criteria.

In cases of prestressed concrete, the initial compressive strain may be subtracted from strain calculated according to Eq-5. In cases of restrained shrinkage and joint-less slabs, the estimated shrinkage strain shall be added to the strain computed from Eq-5. Several methods of strain computation are available. The structural design professional shall select an appropriate method to calculate these tensile strain values. TSMR shall not be used to replace post-tension and pre-stressing strands except as provided in Section 11.3 of this criteria. The addition of TSMR does not change the prestressed design procedure.

12.3 Class C Structure Limitations

12.3.1 Bar reinforcement is not required in any structural member where strains exceeds the Class A or B strain limits but conforms to the Class A or B application limitations listed in Section 3.1 of this criteria. The structural design professional, may, however elect to use a combination of bar reinforcement and TSMR for these applications.

12.3.2 Bar reinforcement is required in any structure not complying with the Class A and B application limitations listed in Section 3.1 of this criteria. The minimum quantity shall be as prescribed in ACI 318-14 Section 9.6.1.2 (ACI 318-11 and -08 Section 10.5.1) or other code-required minimum structural reinforcement for the application.

12.3.3 Unsupported horizontal spans (free-spanning beams or slabs with occupied space above or beneath) shall have the minimum amount of bar reinforcement required by ACI 318 to resist nominal service loads.

12.3.4 Strength provided by non-composite stay-in-place forms for installations not complying with the Class A and B application limitations may be used to satisfy the minimum reinforcement requirement provided the structural design professional designs the forms to provide resistance equal to or greater the resistance than provided by the required bar reinforcement. The TSMR dosage shall be adequate to support the entire load and the contribution of the stay-in-place forms shall not be added to the TSMR capacity.

12.3.5 The requirement for reinforcing bars may be waived based on acceptable data in accordance with Section 11.3 of this criteria.

12.4 Class A and B Hybrid Design

12.4.1 Hybrid design is allowed for Class A and B structural members with no minimum reinforcing bar requirement when the application limits listed in Section 3.1 of this criteria and strain limits in Section 12.2 of this criteria are satisfied.

12.4.2 If Class A or B application limits listed in Section 3.1 of this criteria are satisfied but the strain limit in Section 12.2 of this criteria is exceeded, the structural member may be designed as Class B Hybrid. This process will reduce the strain computed in Section 12.2 of this criteria. The strain limit may be waived if the minimum amount of bar reinforcement as prescribed in ACI 318-14 Section 9.6.1.2 (ACI 318-11 and -08 Section 10.5.1) is provided. Alternatively, the structural design professional may elect to design the structural member as Class C without the need for bar reinforcement.

12.5 Dosage and Compressive Strength Limitations: Minimum and maximum dosages and concrete compressive strengths shall be set at levels consistent with the upper and lower bounds of the tensile testing program. Extrapolation above and below the tested concrete compressive strengths and TSMR counts is not permitted.

12.6 Flexure Limitations: For flexure, standard balanced and tension-controlled strain limits as prescribed in ACI 318-14 Section 21.2.2 (ACI 318-11 and -08 Section 10.3) shall apply.

12.7 Shear Restrictions:

12.7.1 Use of TSMR for replacing shear reinforcement in Class A and Cs structural members is not allowed.

12.7.2 The contribution of plain concrete shall be neglected in applications like shear (do not add V_c to the shear resistance computed for TSMR). The direct tension tests used to characterize the material include the effect of the concrete.

12.7.3 The area in tension shall be taken as the 1.41 x the section width x height minus 4 inches (100 mm). This represents the 45-degree plane between the two layers of original reinforcement.

12.8 Approval: A registered design professional shall approve use of TSMR.

12.9 Precast Concrete: TSMR shall not be used to replace supplemental reinforcing bars placed around openings and tied to lifting points. Precast concrete may be designed as Class B even if the class B application limitations are exceeded based on acceptable data in accordance with Section 11.3 of this criteria.

12.10 Concrete Mixtures: When TSMR is added at the ready-mix plant, a batch ticket signed by a ready-mix representative shall be available to the code official upon request. The delivery ticket shall include, in addition to the items noted in ASTM C94, the type and amount of TSMR added to the concrete mix.

13.0 Evaluation Report Recognition

13.1 General: The Evaluation Report shall include the following:

13.2 Basic information required by Section 4.0 of this criteria including product description, packaging and identification.

13.3 Description of TSMR design classes and application limits in accordance with Section 3.1 of this criteria.

13.4 Design instructions and tables in accordance with Section 11.0 of this criteria.

13.5 Limitations in accordance with Section 12.0 of this criteria.

13.6 Use of TSMR for Class C structural members in structures assigned to Seismic Design Categories C, D, E, and F is outside the scope of this report.

13.7 For design of Class Cs structural members, applicable design provisions from ACI 360.

13.8 Description of qualified fire-resistance-rated assemblies in accordance with Section 4.2 of this criteria.

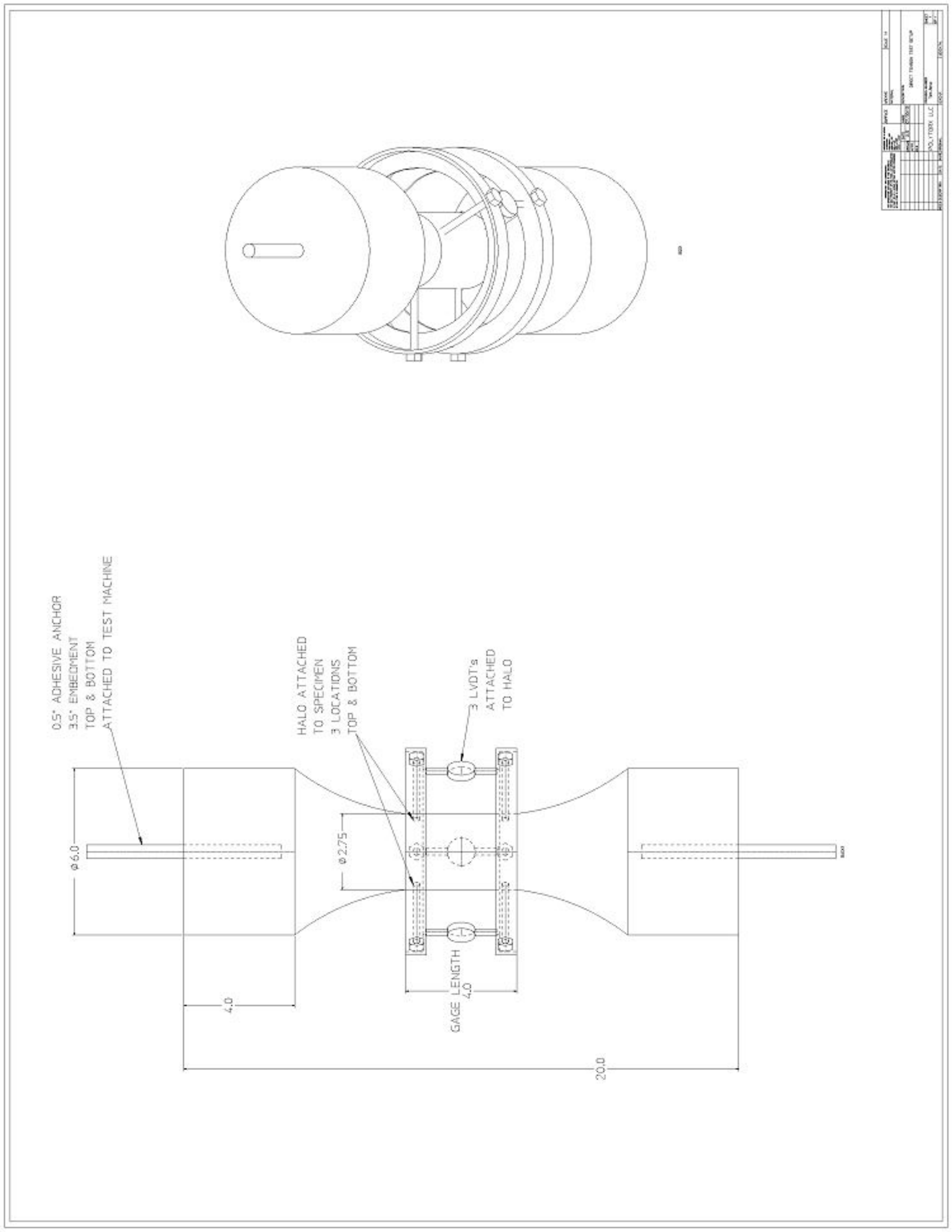

Figure 1 -- Tension Specimen Molds

Table 1: TMSR replacement - Imperial

Fy = 60 ksi	Nominal number of TMSR required					
Nominal area of steel in tension As (in²/ft)	3000 psi		4000 psi		5000 psi	
	Class A & B	Class C & Cs	Class A & B	Class C & Cs	Class A & B	Class C & Cs

Figure 2 – Table 1

Table 2: TMSR dosage rate - Imperial

Number of TMSR per unit area in tension ($TMSR/in^2$)	TMSR dosage rate, H_d (lb/yd^3)											
	3000 psi				4000 psi				5000 psi			
	Class A	Class B	Class C	Class C_s	Class A	Class B	Class C	Class C_s	Class A	Class B	Class C	Class C_s

Figure 3 – Table 2

Table 3: TMSR tensile force - Imperial

Number of TMSR per unit area in tension ($TMSR/in^2$)	Provided TMSR unit tensile stress, ϕF_{ht} (psi)											
	3000 psi				4000 psi				5000 psi			
	Class A	Class B	Class C	Class C_s	Class A	Class B	Class C	Class C_s	Class A	Class B	Class C	Class C_s

Figure 4 – Table 3

Annex A
Test Report Content

1.0 The services performed by the testing laboratory shall be documented by a retrievable report that accurately, clearly, objectively, and unambiguously presents measurements, observations, examinations, and test results in accordance with the reporting requirements of test method(s). Each test or inspection report also shall include the following unless the code, evaluation criteria, or the test standard requirements specify otherwise:

- **1.1** A title, for example, "Report of TSMR Tests;"
- **1.2** The name, address, and contact information of the laboratory.
- **1.3** A unique identification of the report (such as report number), the issue date, a sequential number for each page, and the total number of pages.
- **1.4** The name and address of client.
- **1.5** Description of, condition of, and clear identification of the item tested.
- **1.6** Date test(s) were conducted.
- **1.7** Identification of test standards or description of any non-standard methods used.
- **1.8** Any deviations from, additions to, or exclusions from, the test standard and any other information relevant to the specific test, such as environmental conditions;
- **1.9** Measurements, observations, examinations, and test results, supported by tables, graphs, sketches, and photographs, as appropriate, including a description of the failure mode or condition of item at conclusion of the tests;
- **1.10** Conclusions or summary statements, including, when applicable, a statement indicating whether the product passed or failed the test;
- **1.11** A statement the results apply only to the items tested;
- **1.12** A statement that the report shall not be reproduced, except in full, without the prior written approval of the laboratory; and
- **1.13** Name(s) of individual(s) performing the tests;
- **1.14** A signature and title, or an equivalent identification, of the person(s) accepting responsibility for the content of the report on behalf of the laboratory.
- **1.15** Identification of results obtained from tests subcontracted by the laboratory to others. The laboratory shall not represent the services of others as its own.

2.0 In addition to the requirements of Sections 1.0, 2,0 and 3.0, each test report, where necessary for the proper interpretation or understanding of the report, shall include the following:

- **2.1** Project title and reference designation.
- **2.2** Reference to relevant code, evaluation criteria, or other requirement(s).
- **2.3** A statement indicating compliance with relevant code, evaluation criteria, or other requirement(s).
- **2.4** Other reporting requirements of the evaluation agency, the client, or relevant authority.

3.0 In addition to the requirements of Sections 1.0, 2.0, 3.0 and 4.0, test reports presenting results shall include the following with respect to sampling:

- **3.1** Date of sampling or date sample received, as appropriate.
- **3.2** Clear identification of the material sampled including manufacturer, brand name, lot number, source, or similar unique information, as applicable.
- **3.3** Sampling location, where relevant, using an explicit description, diagram, sketch, or photograph, as applicable.
- **3.4** Identification of sampling methods used, or sampling plan or procedure if a non-standard method was used.
- **3.5** Deviations from, additions to, or exclusions from standard sampling methods or predetermined sampling plans or procedures.
- **3.6** Details of environmental conditions present during the sampling such as rain or freezing weather that may have affected the testing of the sample or the interpretation of the test results.

3.7 If assemblies are tested (structural assemblies, fire-rated assemblies, etc.), identification of the assemblies, preferably with illustrations. The report shall identify the parties constructing the assemblies and shall also address witnessing and/or verifying the construction.

4.0 When interpretations of tests are included in the report, the basis for the interpretations shall be clearly explained. Interpretations commonly include determination of compliance or noncompliance of the results with requirements of the test method or evaluation criteria.

5.0 Material revisions or additions to a report after initial issue shall be made in a further document clearly indicating the revised information and clearly referencing the original report identification. Such revisions or additions shall meet the relevant requirements of Section 2.0.

6.0 Transmission of test reports by electronic means shall follow documented procedures to ensure that the requirements of this evaluation criteria are met and that confidentiality is preserved.

ANNEX B
Method for Calculating the Acceptable Limits for a TSMR Dosage

Using the provisions determined in Section 11.1.3 of this criteria, the coefficient of variation, COV, for the distribution of TSMR micro rebar is

$$COV = f(TSMR\ dosage) \qquad \textbf{(1)}$$

Using Equation B1, the acceptable coefficient of variation can be calculated for any given TSMR dosage in lb/yd^3. Equation 1 can only be used with dosages expressed in lb/yd^3, if a dosage is required for metric units, the desired dosage shall be converted to lb/yd^3 and then used with Equation B1.

To determine the limits, definition of the coefficient of variation shall be computed by Equation B2:

$$COV = \frac{\sigma}{\mu} \qquad (2)$$

Where σ is the standard deviation and μ is the mean. To determine the acceptable TSMR dosage limit, the mean for the TSMR dosage shall be taken as equivalent to the intended TSMR dosage of the concrete mix. For the calculation of an acceptable TSMR dosage limit, one standard deviation shall be taken as the acceptable deviation from the intended TSMR dosage.

By rearranging Equation B2, the acceptable deviation for a given TSMR dosage becomes Equation B3:

$$\sigma = (COV)(\mu) \qquad (3)$$

The lower acceptable dosage limit, LADL, , is then calculated using the Equation B4:

$$LADL = \mu - \sigma \qquad (4)$$

The LADL can then be used as an established acceptable lower bound for an intended TSMR dosage when paired with the TSMR Wash out test. This lower bound ensures that an adequate distribution of the TSMR fibers within the concrete mix is achieved.

A table can be developed to using these calculations showing the oz/cubic foot (grams/Liter) required and included in the ESR for common TSMR dosages. Samples are included (Table B1 and B2).

Specified TSMR Dosage (lb/yd^3)	Coefficient of Variation	Standard Deviation (lb/yd^3)	Lower Dosage Test Limit (oz/ft^3)
5	0.271	2.12	2.16
10	0.212	2.50	4.67
…	…	…	…
60	0.019	2.12	34.89

Table B1. Example Acceptable limits for intended TSMR dosages of a 9 cubic yard truck, English Units

Specified TSMR Dosage (kg/m^3)	Coefficient of Variation	Standard Deviation (kg/m^3)	Lower Dosage Test Limit (g/L)
2.92	0.299	0.87	2.05
5.84	0.260	1.52	4.33
…	…	…	…
35.06	0.063	2.20	32.86

Table B2. Acceptable limits for intended TSMR dosages of a 7 cubic meter truck, SI Units

APPENDIX A
(NONMANDATORY INFORMATION)

1. **General**
   It is recommended that any evaluation report developed in accordance with EC 015 contain instructions and figures similar to what in included herein along with several worked out example problems to assist the designer.

2. **Design in accordance with ACI 318 (Structural Concrete)**
   Designs governed by ACI 318-14 Section 1.10 (ACI 318-11 and -08 are in compliance with Section 1.4) (Approval of special systems of design or construction). For more details, see EC 015 Section 1.0 and ACI Public Discussion, Code Case ACI 318-08/001(12) and 318-11/001(12), Concrete International, V. 35, No. 2, Feb. 2013, p. 67)[v]. Design instructions are provided in Sections 4.1 to 4.4 of this Appendix.

3. **Design in accordance with ACI 360 (Slabs on Grade)**
   Slab on grade design is outside the scope of ACI 318 and alternatively may be done is done in accordance with ACI 360. Design instructions are provided in Section 4.5 of this Appendix.

4. **Design Instructions**

   4.1. **Flexural Design** Follow steps below to compute TMSR dosage using the tables developed in accordance with EC015.

   4.1.1. Determine Design Class using the definitions in EC015 Section 3.1
   A flow chart (Figure 5) simplifies the class selection process[v].

4.1.2. Compute Required Area of Steel

Determine the required area of steel at the centroid of the tension zone (TSMR acts as a rectangular tensile block as shown in Figure 6) with standard design procedures recommended in ACI 318-14 Chapter 6 (ACI 318-11 and -08 Chapter 8) using load and resistance factor design. Use the calculated nominal area of steel in the procedure described in Section 4.1.3 of this Appendix. An appropriate strength reduction factor will be applied to the TMSR design strength.

4.1.3. Table 1: Required TMSR

Use Table 1 to select the minimum number of **TMSR** required to provide the same tensile resistance as the area of steel computed in Appendix A Section 4.1.2. Divide this number by the area of the concrete in tension to obtain the number of **TMSR** required per unit area. This can be either direct tension, flexural tension, or shear.

4.1.4. Table 2: TMSR Dosage

Use Table 2 to select the minimum **TMSR** dosage required to ensure the number of **TMSR** per unit area (as determined in Appendix A Section 4.1.3) are provided in the tensile region of the concrete. The **TMSR** dosage listed in the table is calibrated using LRFD methods.

4.1.5. Table 3: TMSR tensile force

Use Table 3 to select the provided **TMSR** unit tensile strength. This value can be multiplied by the effective area in tension to compute the total tensile resistance.

4.1.6. **Compute strain in the composite**

For Class A and B use Table 3 to select the provided **TMSR** unit tensile strength and calculate the average strain with Equation A1:

Equation A1 $\varepsilon \cong \textbf{TMSR}\text{tensile stress}/E_{CT}$

Where:

- E_{ct} is the tensile modulus of elasticity of TMSR concrete estimated as $57000\sqrt{f'c}$ (psi) or $4200\sqrt{f'c}$ (MPa).
- ε the average concrete tensile strain

4.1.7. Pre- or post-tensioned concrete

With pre- or post- tensioned concrete, the initial compressive strain may be subtracted from the average strain calculated in Equation A1.

4.1.8. Restrained shrinkage

In cases of restrained shrinkage, the shrinkage strain shall be added to the average strain computed in Equation A1.

4.2. Shear: The same method as above is used for shear and torsion reinforcement. The Area in tension should be taken as no more than the 1.41 x the section width x height minus twice the neutral axis depth. When replacing both bending and shear reinforcement the higher of the two dosages governs the design.

4.3. Class A And B Strain Limits: The average tensile strain (Appendix A Section 4.1.6-4.17 and 4.18) in the concrete shall not exceed limits established in EC 015 Section 12.2.

4.4. Hybrid Design

A combination of standard reinforcement and **TMSR** may be used. For Hybrid Design, reduce the area of steel computed in Section 4.1 of this criteria by the cross sectional area of the rebar that will remain prior to determining the required minimum number of **TMSR** using Table 1.

4.5. ACI 360 Design Instructions

4.5.1. Class A and B Design in accordance with ACI 360-10 Section 11.3.3.2 (Elastic Design Method). Substitute $\frac{\text{Table 8 Value}}{f_r}$ where $\frac{R_{e,3}}{100}$ is used in ACI 360-10 Section 11.3.3.2 equations. All other calculations remain the same.

4.5.2. Class Cs Design with Yield Line Methods ACI 360-10 Section 11.3.3.3, Substitute $\frac{\text{Table 8 Value}}{f_r}$ where $\frac{R_{e,3}}{100}$ is used in ACI Section 11.3.3.3 equations. All other calculations remain the same.

4.6. **Limitations/Restrictions**

All designs are subject to the limitations outlined in Section 12.0 of this criteria.

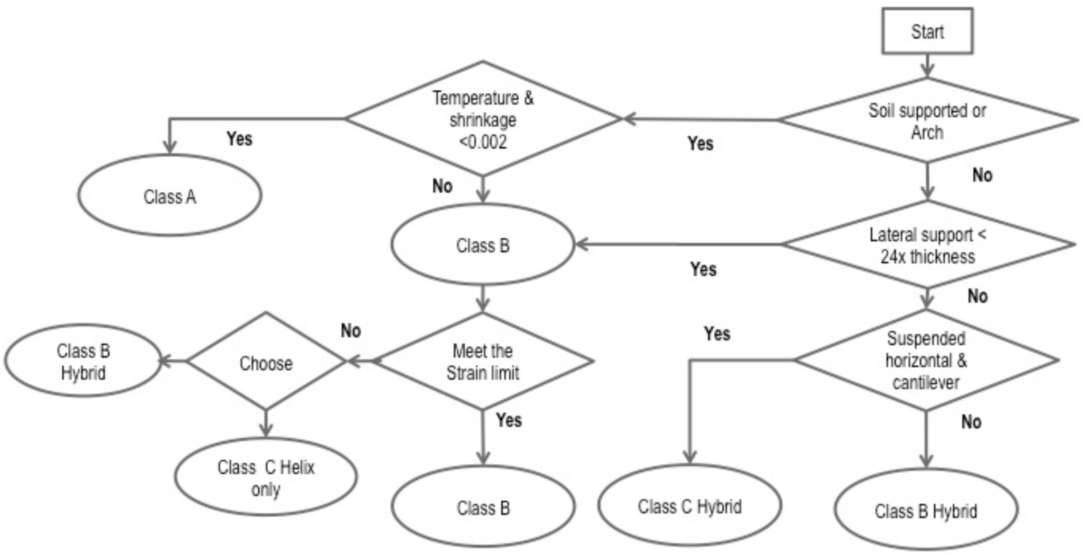

Figure 5: TSMR Class Selection Flow Chart

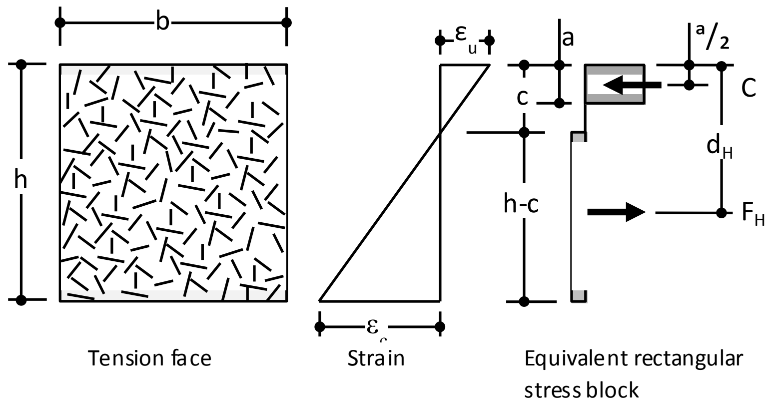

Figure 6: TMSR Flexural Stress Block

[i] Lagoudas, Dimitris L., and Walter E. Haisler, "Introduction to Conservation Principles and Applications in Continuum Mechanics," Summer 2002, 450 pages. <http://aeweb.tamu.edu/haisler/engr214/Word _Lecture_Notes_by_Chapter/chapter12- part1.doc>

[ii] Dupont, D and Vandewalle, L, (2005) Distribution of steel fibres in rectangular sections. Cement and Concrete Composites 27(3):391-398.

[iii] MacGregor, J.G., “Safety and Limit States Design for Reinforced Concrete,” Canadian Journal of Civil Engineering, V. 3, No. 4, Dec. 1976, pp. 484-513.

[iv] Public Discussion, Code Case ACI 318-08/001(12) and 318-11/001(12), Concrete International, V. 35, No. 2, Feb. 2013, p. 67.

[v] Pinkerton, L and Novak, J & Stecher, J “Twisted Steel Micro-Reinforcement”, Concrete International, October 2013, pp 57-61).