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ACCEPTANCE CRITERIA FOR MASONRY AND CONCRETE STRENGTHENING USING FIBER-REINFORCED CEMENTITIOUS MATRIX (FRCM) COMPOSITE SYSTEMS

AC434

Approved October 2011

PREFACE

Evaluation reports issued by ICC Evaluation Service, LLC (ICC-ES), are based upon performance features of the International family of codes. (Some reports may also reference older code families such as the BOCA National Codes, the Standard Codes, and the Uniform Codes.) Section 104.11 of the *International Building Code®* reads as follows:

> **The provisions of this code are not intended to prevent the installation of any materials or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been approved. An alternative material, design or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability and safety.**

This acceptance criteria has been issued to provide interested parties with guidelines for demonstrating compliance with performance features of the codes referenced in the criteria. The criteria was developed through a transparent process involving public hearings of the ICC-ES Evaluation Committee, and/or on-line postings where public comment was solicited.

New acceptance criteria will only have an "approved" date, which is the date the document was approved by the Evaluation Committee. When existing acceptance criteria are revised, the Evaluation Committee will decide whether the revised document should carry only an "approved" date, or an "approved" date combined with a "compliance" date. The compliance date is the date by which relevant evaluation reports must comply with the requirements of the criteria. See the ICC-ES web site for more information on compliance dates.

If this criteria is a revised edition, a solid vertical line (│) in the margin within the criteria indicates a technical change from the previous edition. A deletion indicator (→) is provided in the margin where wording has been deleted if the deletion involved a technical change.

ICC-ES may consider alternate criteria for report approval, provided the report applicant submits data demonstrating that the alternate criteria are at least equivalent to the criteria set forth in this document, and otherwise demonstrate compliance with the performance features of the codes. ICC-ES retains the right to refuse to issue or renew any evaluation report, if the applicable product, material, or method of construction is such that either unusual care with its installation or use must be exercised for satisfactory performance, or if malfunctioning is apt to cause injury or unreasonable damage.

NOTE: The Preface for ICC-ES acceptance criteria was revised in July 2011 to reflect changes in policy.

Acceptance criteria are developed for use solely by ICC-ES for purpose of issuing ICC-ES evaluation reports.

ACCEPTANCE CRITERIA FOR MASONRY AND CONCRETE STRENGTHENING USING FIBER-REINFORCED CEMENTITIOUS MATRIX (FRCM) COMPOSITE SYSTEMS (AC434)

1.0 INTRODUCTION

1.1 Purpose: The purpose of this acceptance criteria is to establish requirements for recognition of fiber-reinforced cementitious matrix (FRCM) composite systems, used for the strengthening of masonry and concrete structures, in ICC Evaluation Service, LLC (ICC-ES), evaluation reports under the 2012 and 2009 *International Building Code*® (IBC). The basis of recognition is IBC Section 104.11.

The reason for the development of this criteria is to provide guidelines for the evaluation of alternative strengthening methods for masonry and concrete structural elements, where the codes do not provide requirements for testing and determination of structural capacity, reliability and serviceability of these products.

1.2 Scope: This criteria applies to passive fiber-reinforced cementitious matrix (FRCM) composite systems used to strengthen existing masonry and concrete structures. Properties evaluated include FRCM material properties; axial, flexural and shear capacities of the FRCM system; performance of the FRCM system under environmental exposures; performance under exposure to fire conditions; and structural design procedures.

1.3 Referenced Codes and Standards:

1.3.1 2012 and 2009 *International Building Code*® (IBC), International Code Council.

1.3.2 ACI 318-11 (2012 IBC), Building Code Requirements for Structural Concrete and Commentary, American Concrete Institute.

1.3.3 ACI 318-08 (2009 IBC), Building Code Requirements for Structural Concrete and Commentary, American Concrete Institute.

1.3.4 ASCE 41-06: Seismic Rehabilitation of Existing Buildings, American Society of Civil Engineers.

1.3.5 TMS 402-11/ACI 530-11/ASCE 5-11 (2012 IBC), Building Code Requirements for Masonry Structures, American Concrete Institute.

1.3.6 TMS 402-08/ACI 530-08/ASCE 5-08 (2009 IBC), Building Code Requirements for Masonry Structures, American Concrete Institute.

1.3.7 ASTM C 138-10b, Standard Test Method for Density (Unit Weight), Yield, and Air (Gravimetric) of Concrete, ASTM International.

1.3.8 ASTM C 157-08, Standard Test Method for Length Change of Hardened Hydraulic Mortar and Concrete.

1.3.9 ASTM C 387/C 387M-11, Standard Specification for Packaged, Dry, Combined Materials for Mortar and Concrete, ASTM International.

1.3.10 ASTM C 947-03 (2009), Standard Test Method for Flexural Properties of Thin-Section Glass-Fiber-Reinforced Concrete (Using Simple Beam with Third-Point Loading), ASTM International.

1.3.11 ASTM C 1583/C 1583M-04^{e1}, Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method), ASTM International.

1.3.12 ASTM D 1141-98 (2008), Standard Practice for Preparation of Substitute Ocean Water, ASTM International.

1.3.13 ASTM D 2247-11, Standard Practice for Testing Water Resistance of Coatings in 100% Relative Humidity, ASTM International.

1.3.14 ASTM D 2344/D 2344M-00 (2006), Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates, ASTM International.

1.3.15 ASTM D 3165-07, Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single Lap-Joint Laminated Assemblies, ASTM International.

1.3.16 ASTM E 4-10, Standard Practices for Force Verification of Testing Machines, ASTM International.

1.3.17 ASTM E 83-10a, Standard Practice for Verification and Classification of Extensometers, ASTM International.

1.3.18 ASTM E 104-02 (2007), Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions, ASTM International.

1.4 Definitions:

1.4.1 Design Values: The FRCM composite system's load and deformation design capacities that are based on load and resistance factor design (strength design) method.

1.4.2 FRCM Composite Material: A fiber-reinforced cementitious matrix (FRCM) is a composite material consisting of a sequence of one or more layers of cement-based matrix reinforced with fibers in the form of open grid (mesh). When adhered to concrete or masonry structural members, they form an FRCM system. Components are:

1.4.2.1 Structural Reinforcement Grid: Open grid (mesh) of strands made of fibers [i.e., aramid, alkali resistant (AR) glass, carbon, and polyparaphenylene benzobisoxazole (PBO)], consisting of primary direction (PD) and secondary direction (SD) strands connected perpendicularly. The typical strand spacing of PD and SD strands is less than one inch (25.4 mm).

1.4.2.2 Cement-based Matrix: A polymer-modified cement-based binder (mortar) that holds in place the structural reinforcement grids in FRCM composite material.

1.4.3 Cracking Load and Displacement: Load and displacement at which the moment-curvature relationship of the masonry or concrete member first changes slope or at which the cracking moment as defined in ACI 318, Section 9.5.2.3, or TMS 402, Section 3.3.5.5, is reached, whichever occurs first.

1.4.4 Yielding Load and Displacement**:** Load and displacement at which longitudinal steel reinforcement of the reinforced masonry or concrete member reaches its yield strength as defined in ACI 318, Section 2.2.

1.4.5 Passive Composite Systems: Composite systems that are not post-tensioned after installation are considered as passive composite systems.

1.4.6 Rational Analysis and Design Procedure: A method of structural analysis and design that takes into account equilibrium, structural stability, geometric compatibility, and both short- and long-term material properties.

1.4.7 FRCM Composite Material Configuration: A combination of all applicable parameters that affect the performance of the FRCM composite material, such as layers, thicknesses, components, bonding agents, etc.

2.0 BASIC INFORMATION

2.1 General: The following information shall be submitted:

2.1.1 Product Description**:** A detailed description of the FRCM system is needed, including the following items:

1. Description and identification of the product or system.
2. Restrictions or limitations on use.

2.1.2 Installation Instructions: Instructions shall include the following items.

1. Description of how the product or system will be used or installed in the field.
2. Procedures establishing quality control in field installations.
3. Requirements for product handling and storage.
4. For installations that depend on bond between the system and the substrate, on-site testing of bond to the substrate is required.

2.1.3 Packaging and Identification: A description of the method of packaging and field identification of the system components. Identification provisions shall include the evaluation report number and the name or logo of the inspection agency.

2.1.4 Field Preparation: A description of the methods of field-preparation, such as proportioning and mixing, application, curing, and finishing.

2.2 Testing Laboratories: Testing laboratories shall comply with the ICC-ES Acceptance Criteria for Test Reports (AC85) and Section 4.2 of the ICC-ES Rules of Procedure for Evaluation Reports.

2.3 Test Reports: Test reports shall comply with AC85.

2.4 Product Sampling: Products shall be sampled in accordance with Section 3.1 of AC85.

3.0 TEST AND PERFORMANCE REQUIREMENTS

3.1 Qualification Test Plan: A qualification test plan shall be submitted for ICC-ES staff review prior to any testing. The intent of testing is to verify the design equations and assumptions used in the engineering analysis and presented in the Design Criteria Report referenced in Section 8.0. All or part of the tests described in this section, and any additional tests identified by the applicant for special features of the product or system, shall be specified.

Overall, qualification testing shall provide data on material properties, force and deformation limit states, including failure modes of the composite material and each structural system described in Sections 4.0 and 5.0, to support a rational analysis and design procedure. The specimens shall be constructed under conditions specified by the evaluation report applicant to be recognized in the ICC-ES evaluation report, including curing. The specimens shall be prepared to verify the range of the FRCM composite material configurations (layers, thickness, components, bonding agents, etc.) specified by the applicant. Tests shall simulate the anticipated range of loading conditions, load levels, deflections, and ductility.

4.0 MATERIAL TEST METHODS

4.1 General: Required FRCM composite material physical, mechanical, and durability properties are described in this section along with the test procedures. Properties obtained from these tests shall be considered in the design criteria and limitations described in Section 8.0. Evaluation of test results shall be made on the basis of the average values obtained from a minimum of five specimens for each condition. Table 1 offers a summary of the minimum material tests required for each FRCM material system.

4.2 Physical and Mechanical Properties of FRCM Composite Material:

4.2.1 Drying Shrinkage: A panel of FRCM material for this test shall be cured, tested, and measured in accordance with general procedures outlined in ASTM C 157. Coupon specimens shall be cut from larger size panels. Five coupon specimens shall be used for drying shrinkage measurements for each FRCM configuration. The size of specimens shall be 3 by 16 inches (76 by 400 mm). Caution shall be used to eliminate bending error that may occur.

4.2.2 Void Content: Five FRCM specimens shall be tested for each FRCM configuration. The size of specimens shall be 3 by 6 inches (75 by 152 mm). The tests shall be conducted in accordance with ASTM C 138. Air content and unit weight shall be measured.

4.2.3 Tensile Strength: Tensile testing to determine the tensile strength, elongation, and modulus of elasticity shall be conducted on coupons cut from FRCM panels laid up using a procedure similar to that in the actual in-service application and according to the applicant's instructions. The test procedures shall comply with the "Tensile Testing of Fiber-Reinforced Cementitious Matrix (FRCM) Composite Specimens" included in Annex A. Tests shall be conducted for both primary and secondary grid directions, if different and required in the structural application. A minimum of five specimens are required for each FRCM configuration.

4.2.4 Composite Interlaminar Shear Strength: Composite interlaminar shear strength tests on FRCM panels shall follow general procedures of ASTM D 2344. Alternatively, test procedures of ASTM C 947 can be adopted for FRCM in conjunction with provisions of ASTM D 2344 for interpretation of results and reporting regarding interlaminar related issues. A minimum of five specimens are required for each FRCM configuration.

4.3 Properties of Mortar Matrix: Mortar used in FRCM composite material as matrix shall comply with ASTM C 387/C 387M, which covers the production, properties, packaging, and testing of packaged, dry, combined materials for mortars. Normal-strength mortar shall have minimum compressive strengths of 2,500 and 3,500 psi (17.0 and 24.0 MPa) at seven and 28 days, respectively. A minimum of five specimens are required for each mortar type to be recognized in the ICC-ES evaluation report.

4.4 Freezing and Thawing:

4.4.1 Procedure: Freezing and thawing conditioning is introduced for both tension FRCM panel specimens (Section 4.2.3) and interlaminar shear FRCM specimens (Section 4.2.4). For each specimen type, five specimens shall be conditioned and five shall be kept at ambient temperature as benchmarks. A total of twenty specimens is required. The size of specimens shall be the same as that required for tensile testing (described in Section 4.2.3). Ten samples shall be conditioned for one week in a humidity chamber [100% humidity, 100°F (37.7°C)]. These specimens shall then be subjected to twenty freeze-thaw cycles. Each cycle consists of a minimum of four hours at 0°F (-18°C), followed by 12 hours in a humidity chamber [100 percent humidity, 100°F (37.7°C)].

4.4.2 Conditions of Acceptance: At the end of freeze/thaw cycles, the specimens shall be visually examined for surface changes such as erosion, scaling, cracking, and crazing. The samples shall then be tested for tensile strength and interlaminar shear. Specimens are tested in their primary direction. Freeze/thaw specimens shall retain at least 85 percent of the tensile and shear properties of control specimens.

4.5 Aging: These tests shall be considered in design criteria and limitations.

4.5.1 Procedure: Both wet and dry FRCM panel specimens are aged in accordance with Table 2. Both exposed and control specimens are then tested for tensile strength, tensile modulus, elongation, and interlaminar shear strength in accordance with Sections 4.2.3 and 4.2.4. Specimens shall be tested in their primary direction. A minimum of five specimens for each FRCM configuration are required.

4.5.2 Conditions of Acceptance: Control and exposed specimens shall be visually examined using 5x magnification. Surface changes affecting performance, such as erosion, cracking, and crazing, are unacceptable. The exposed specimens shall retain the percentage of tensile and interlaminar shear properties generated on control specimens noted in Table 2.

4.6 Fuel Resistance: Ten FRCM panel specimens shall be prepared of which five are exposed to diesel fuel reagent for a minimum of four hours. After conditioning, the specimens shall be tested in accordance with Section 4.2.3 for tensile strength, tensile modulus and elongation. Specimens shall be tested in their primary direction. Specimens shall retain at least 85 percent of the tensile properties of control specimens. A minimum of five specimens are required for each FRCM configuration.

4.7 Lap Tensile Strength: When applying FRCM composite materials for strengthening of structural masonry or concrete members, splices and laps will be necessary for the grid reinforcement. To determine the relative tensile strength at the grid overlap area, lap tensile strength testing is required. This test will be particularly useful if the joint configuration closely simulates the actual joint in material field application.

It is understood that in application of multilayer FRCM composite materials, the laps shall be staggered from the laps in the nearby layer. Laps in one layer shall start with a minimum distance equivalent to the development length of fiber strands in the matrix established by the applicant, or larger.

4.7.1 Procedure: The general test procedures of ASTM D 3165 shall be used with exposures listed in Table 2. Fifty test coupons shall be cut from a larger FRCM material panel. The panel shall consist of only one layer of FRCM material. The grid in the panel shall be two-piece with an overlap length in the middle. The lap length may vary, but a minimum 2-inch (51 mm) lap length is recommended. The coupons shall be cut having the same dimensions as described in the tensile strength testing process in Annex A, such that the overlap length is positioned at mid-length. Curing, specimen preparation, tab preparation and properties, tab installation and grip conditions shall follow those described in the tensile strength testing in Annex A. Multiple-layer tests can also be considered with a configuration that serves the purpose of this test.

4.7.2 Conditions of Acceptance: For unconditioned specimens (control), lap tensile strength shall be not less than that of a specimen with continuous reinforcement. The exposed specimens shall retain the percentage of tensile strength generated on control specimens noted in Table 2.

4.8 Bond Strength:

4.8.1 Procedure: For tensile bond testing, forty FRCM materials shall be prepared. The FRCM material shall be applied onto the substrate [minimum 2.5 inches (63 mm) thick] in accordance with the applicant's instructions. Thirty specimens shall then be exposed to conditions presented in Table 2. Ten specimens shall be kept in standard laboratory conditions as control specimens. The test shall follow the general procedures of the ASTM C 1583. The pull-off strength shall be computed based on the maximum indicated load. A minimum of five specimens for each FRCM configuration are required.

4.8.2 Conditions of Acceptance: The predominant mode of failure shall be cohesive failure at a strength of at least 200 psi (1.38 MPa) for the control specimen. The exposed specimens shall retain the percentage of bond strength generated on control specimens noted in Table 2.

4.9 Fire-resistance-rated Construction: The effect of the FRCM material system on fire-resistance rated construction shall be evaluated according to Section 703 of the IBC.

4.10 Interior Finish: The classification of the FRCM composite system as an interior finish shall be determined according to Section 803 of the IBC.

5.0 STRUCTURAL PERFORMANCE TEST METHODS

5.1 General: Tests required to validate the performance of structural components are described in this section, along with the recommended procedures. Evaluation of test results shall be made on the basis of the values obtained from a minimum of three identical specimens. The deviation of any strength value obtained from any single test shall not vary from the average value for all tests by more than 15 percent. If such deviation from the average value for any test exceeds 15 percent, then additional tests shall be performed until the deviation of any test does not exceed 15 percent or a minimum of six tests have been performed.

5.2 Masonry:

5.2.1 Wall Flexural Tests (Out-of-plane Load):

5.2.1.1 Configuration: Wall flexural specimens shall be configured to induce out-of-plane flexural limit states and failure modes as related to FRCM performance. Extremes of dimensional, FRCM reinforcing, and masonry compressive strength parameters of the masonry wall to be strengthened by the FRCM shall be considered.

5.2.1.2 Procedure: For seismic or wind-load application, the lateral load procedure shall conform to Figure 1. For gravity (non-dynamic) loading application, the load may be monotonically applied until the strengthening system is damaged, its capacity is reached, or desired limit states are achieved. Specimens may be axially loaded to consider effects of axial loads. The loading in the out-of-plane direction may be applied at third-points, by airbags or by other means representing actual conditions.

5.2.2 Wall Shear Tests (In-plane Shear):

5.2.2.1 Configuration: Wall shear specimens shall be configured to induce in-plane shear limit states or failure modes as related to FRCM performance. Extremes of dimensional, FRCM reinforcing and masonry compressive strength parameters of the masonry wall to be strengthened by the FRCM shall be considered.

5.2.2.2 Procedure: For seismic or wind-load application, the load procedure shall conform to Figure 1. For non-dynamic loading application, the lateral load may be monotonically applied until the strengthening system is damaged, its capacity is reached, or desired limit states are achieved. Specimens also may be axially loaded to consider effects of axial loads.

5.3 Concrete:

5.3.1 Beams:

5.3.1.1 Flexural Tests:

5.3.1.1.1 Configuration: Beam spans shall be configured to induce flexural limit states or failure modes as related to FRCM performance. Either simple or rigid supports are permitted. Extremes of dimensional, FRCM reinforcing, and compressive strength parameters of the concrete beams to be strengthened by FRCM shall be considered.

5.3.1.1.2 Procedure: For seismic or wind-load application, the lateral load procedure shall conform to Figure 1. For gravity (non-dynamic) loading application, the load may be monotonically applied. The limit states shall be determined based on material properties and maximum concrete compression strain of 0.003.

5.3.1.2 Shear Tests:

5.3.1.2.1 Configuration: Beam spans shall be configured to induce shear limit states or failure modes as related to FRCM performance. Either simple or rigid supports are permitted. Extremes of dimensional, FRCM reinforcing, and compressive strength parameters of the concrete beams to be strengthened by FRCM shall be considered.

5.3.1.2.2 Procedure: For seismic or wind loading, the lateral load procedure shall conform to Figure 1. For gravity loading, the load may be monotonically applied. The limit states shall be determined based on geometric and material properties.

5.3.2 Beam-to-column Joints:

5.3.2.1 Configuration: The beam-to-column joint shall be configured to induce joint-related limit states or failure modes as related to FRCM performance. The column portion may be constructed to represent a section between inflection points. Extremes of dimensional, FRCM reinforcing and compressive strength parameters of the concrete beam-to-column joins to be strengthened by FRCM shall be considered.

5.3.2.2 Procedure: The lateral load procedure shall conform to Figure 1. A vertical load shall be continuously applied and varied within a specified range. The limit states shall be determined based on geometric and material properties.

5.3.3 Columns:

5.3.3.1 Pure Axial Tests:

5.3.3.1.1 Configuration: Column specimens shall be configured to induce axial compression limit states or failure modes as related to FRCM performance. Extremes of dimensional, FRCM reinforcing, and strength parameters of the concrete columns to be strengthened by FRCM shall be considered.

5.3.3.1.2 Procedure: The load shall be monotonically applied. The limit states shall be determined based on geometric, material properties and column end support conditions.

5.3.3.2 Flexural Tests:

5.3.3.2.1 Configuration: Column specimens shall be configured to induce flexural limit states or failure modes as related to FRCM performance. Either cantilever or double fixity (reverse curvature) is permitted in specimens. Extremes of dimensional, FRCM reinforcing, and strength parameters of the concrete columns to be strengthened by FRCM shall be considered.

5.3.3.2.2 Procedure: For seismic or wind-load applications, the lateral load procedure shall conform to Figure 1. For gravity (non-dynamic) loading applications, the load may be monotonically applied. Axial loads within a specific range shall be applied. The limit states shall be determined based on geometric, material properties and column end support conditions.

5.3.3.3 Shear Tests:

5.3.3.3.1 Configuration: Column specimen spans shall be configured to induce shear limit states or failure modes as related to FRCM performance. Double fixity (reverse curvature) is required. Extremes of dimensional, FRCM reinforcing, and compressive strength parameters of the concrete columns to be strengthened by FRCM shall be considered.

5.3.3.3.2 Procedure: For seismic or wind-load application, the lateral load procedure shall conform to Figure 1. For gravity (non-dynamic) loading application, the load may be monotonically applied. Axial loads within a specific range shall be applied. The limit states shall be determined based on geometric, material properties and column end support conditions.

5.3.4 Slabs:

5.3.4.1 Configuration: Slab spans shall be configured to include flexural limit states or failure modes as related to FRCM performance. Either simple or rigid supports are permitted. Extremes of dimensional, FRCM reinforcing and compressive strength of the concrete slabs to be strengthened by FRCM shall be considered.

5.3.4.2 Procedure: For gravity (non-dynamic) loading application, the load may be monotonically applied. The limit states shall be determined based on material properties and maximum concrete compression strain of 0.003.

6.0 QUALITY CONTROL

6.1 Manufacturing: Quality control procedures during manufacture of the system components as described in Section 1.4.2 shall be described a quality documentation complying with the ICC-ES Acceptance Criteria for Quality Documentation (AC10), and there shall be inspections by an inspection agency accredited by the International Accreditation Service, Inc. (IAS), or otherwise acceptable to ICC-ES. A qualifying inspection shall be conducted at each manufacturing facility when required by the ICC-ES Acceptance Criteria for Inspections and Inspection Agencies (AC304).

6.2 Installation and Special Inspection: All installations shall be done by applicators approved by the report applicant. The quality assurance program shall be documented. Special inspection is required and shall comply with Section 1704 of the IBC. Duties of the special inspector shall be prepared by the report applicant, and included in the evaluation report. The maximum debonded area permitted after installation of bonded FRCM systems shall be specified by the applicant.

7.0 FINAL SUBMITTAL

7.1 Contents: The final submittal shall consist of a test report or test reports, and a design criteria report, as described in this section. The final submittal shall include the qualification plan described in Section 3.0 of this acceptance criteria. Contents of the final submittal are described in the Sections 7.2 and 7.3.

7.2 Test Report: The testing laboratory shall report on the qualification testing performed according to the approved test plan. Besides the information requested in Section 2.4, the test report shall include the following:

1. Information noted in the referenced standard.
2. Description of test setup.
3. Rate and method of loading.
4. Deformation and strain measurements.
5. Modes of failure.

7.3 Design Criteria Report: The report shall include a complete analysis and interpretation of the qualification test results. Design stress and strain criteria for masonry or concrete members shall be specified based on the analysis, but shall not be higher than specified in Section 8.0.

Design stresses and strains shall be based on a characteristic value approach verified by test data. The drying shrinkage values determined in Section 4.0 shall be considered in the design procedure. The design shall consider, if applicable, secondary stresses resulting when dead loads are relieved during application and subsequently reapplied. Adoption of the minimum acceptable standards for design outlined in Section 8.0 does not eliminate the need for structural testing. Situations not covered in Section 8.0 shall be subject to special considerations and testing, and design values shall be compatible with the conservative approach adopted in Section 8.0.

8.0 MINIMUM ACCEPTABLE DESIGN CRITERIA

8.1 General: Design procedures shall be in accordance with Chapter 19 or 21 of the IBC, as applicable, except as modified in this section. FRCM material properties to be used for design as described in this section are obtained from Section 4.0. The value of any material property to be used in the design equations of this section is defined as the average value minus three times the standard deviation. The limit state design capacities as determined in accordance with Section 8.0 of this criteria cannot exceed the five percent fractile values of the capacities obtained experimentally in accordance with Section 5.0.

8.2 Masonry:

8.2.1 Flexural Strength Enhancement: The FRCM composite material bonded to surfaces of masonry may be used to enhance the design flexural strength out of the plane of the wall by acting as additional tension reinforcement. In such cases, the section analysis shall be based on normal assumptions of strain compatibility between masonry, steel reinforcement (if any), and FRCM composite material. The out-of-plane flexural strength of a (reinforced or unreinforced) masonry wall depends on the controlling failure mode. Failure modes for an FRCM-strengthened wall include:

- Crushing of the masonry in compression
- Debonding of the FRCM from the masonry substrate (FRCM debonding)
- Tensile yielding of the steel reinforcement
- Tensile rupture of FRCM material

The effective tensile strain level in the FRCM composite material attained at failure, ε_{fe}, shall be limited to the design tensile strain of the FRCM composite material, ε_{fd}, defined in Equation (1):

$$\varepsilon_{fd} = 0.7\, \varepsilon_{fu} \leq 0.012 \quad (1)$$

where ε_{fu} is the ultimate tensile strain of the FRCM composite material. The effective tensile stress level in the FRCM reinforcement attained at failure, f_{fe}, shall be calculated in accordance with Equation (2):

$$f_{fe} = 0.85 \cdot E_f \cdot \varepsilon_{fe} \text{ with } \varepsilon_{fe} \leq \varepsilon_{fd} \quad (2)$$

where E_f is the tensile modulus of elasticity of the cracked FRCM composite material. Fiber strands shall be oriented perpendicular to the direction of the applied bending moment and shall not have a misalignment of more than 5 degrees.

The design flexural strength shall be calculated in accordance with Equation (3).

$$\phi_m M_n = \phi_m (M_m + M_f) \quad (3)$$

where M_n is the nominal flexural strength; M_m and M_f are the contribution of the reinforced masonry and the FRCM composite material to the nominal flexural strength, respectively. In the case of unreinforced masonry, only the term M_f is considered. The strength reduction factor for flexure, ϕ_m, is equal to 0.6 for both reinforced and unreinforced masonry.

For the computation of M_n, when the FRCM composite material is applied on both sides of the wall, the contribution of FRCM in the compression side is neglected.

FRCM application does not contribute to the enhancement of the nominal out-of-plane shear strength of the masonry wall which shall be calculated according to TMS 402. A minimum development length of 6 inches (152 mm) shall be considered.

8.2.1.1 Limitations: In the case of unreinforced masonry, when subjected to out-of-plane loading, the wall behaves as a simply supported element or very nearly so, and the influence of wall arching mechanisms can be neglected. An arching mechanism can potentially develop in a wall with a height-to-thickness (H/t) ratio of less than 8 when the wall is built between stiff supports. The influence of arching in the out-of-plane behavior decreases for walls with H/t ratios greater than 14. As a reference, Tables 7-5 and 7-10 of ASCE 41 provide H/t ratios where an unreinforced masonry wall does not need to be analyzed for out-of-plane seismic forces and, therefore, does not require strengthening. For conventionally reinforced masonry walls, to limit the total force per unit width transferred to the masonry, the increment in flexural strength provided by the FRCM reinforcement shall not exceed 50 percent of the capacity of the structure without strengthening.

8.2.2 Shear Strength Enhancement: The FRCM composite material bonded to surfaces of masonry may be used to enhance the design shear strength in the plane of the wall by acting as shear reinforcement.

The design tensile strain in the FRCM shear reinforcement, ε_{fv}, shall be calculated by Equation (4):

$$\varepsilon_{fv} = 0.4\, \varepsilon_{fu} \leq 0.004 \quad (4)$$

The design tensile strength in the FRCM shear reinforcement, f_{fv}, shall be calculated in accordance with Equation (5):

$$f_{fv} = 0.75 \cdot E_f \cdot \varepsilon_{fv} \quad (5)$$

FRCM shall be applied on both sides of the wall with primary fiber strands oriented perpendicular to the applied shear force. Fiber strands shall not have a misalignment of more than 5 degrees.

The design shear strength shall be calculated in accordance with Equation (6).

$$\phi_v V_n = \phi_v (V_m + V_f) \quad (6)$$

where V_n is the nominal shear strength; V_m and V_f are the contribution of the (unreinforced or reinforced) masonry and the FRCM composite material to the nominal shear strength, respectively. V_m is calculated in accordance with TMS 402. V_f is calculated as defined in Equation (7):

$$V_f = 2\, n\, A_f\, L\, f_{fv} \quad (7)$$

where A_f *is* the area of the grid reinforcement by unit width effective in shear, n is the number of layers of grid reinforcement, and L is the length of the wall in the direction of the applied shear force. The strength reduction factor for shear, ϕ_v, is equal to 0.75. A minimum development length of 6 inches (152 mm) shall be considered.

8.2.2.1 Limitations: To limit the total force per unit width transferred to the masonry, the increment in shear strength provided by the FRCM reinforcement shall not exceed 50 percent of the capacity of the structure without strengthening for both unreinforced and conventionally reinforced masonry walls. Strengthening is limited to maximum wall thickness of 12 inches (305 mm).

8.3 Concrete:

8.3.1 Flexural Strength Enhancement of Reinforced Concrete Members: The FRCM composite material bonded to surfaces of reinforced concrete members may be used to enhance the design flexural strength of sections by acting as external tension reinforcement. In such cases, section analysis shall be based on the following normal assumptions: (a) plane sections remain plane after loading; (b) the bond between the FRCM and the substrate remains effective; (c) the maximum usable compressive strain in the concrete is 0.003; (d) FRCM has a linear elastic behavior to failure.

The flexural strength of a reinforced concrete section depends on the controlling failure mode. Failure modes for an FRCM-strengthened section include:

- Crushing of the concrete in compression before yielding of the reinforcing steel.
- Yielding of the steel in tension followed by concrete crushing.
- Shear/tension delamination of the concrete cover (cover delamination).
- Debonding of the FRCM from the concrete substrate (FRCM debonding).
- Tensile rupture of FRCM material.

The effective tensile strain level in the FRCM reinforcement attained at failure, ε_{fe}, shall be limited to the design tensile strain of the FRCM composite material, ε_{fd}, defined in Equation (8):

$$\varepsilon_{fd} = 0.7\ \varepsilon_{fu} \leq 0.012 \tag{8}$$

The effective tensile stress level in the FRCM reinforcement attained at failure, f_{fe}, in the FRCM reinforcement shall be calculated in accordance with Equation (9):

$$f_{fe} = 0.85\ E_f\ \varepsilon_{fe} \quad \text{where} \quad \varepsilon_{fe} \leq \varepsilon_{fd} \tag{9}$$

Fiber strands shall be oriented parallel to the major axes of the member and shall not have a misalignment of more than 5 degrees.

The design flexural strength shall be calculated in accordance with Equation (10).

$$\phi_m\ M_n = \phi_m\ (M_s + M_f) \tag{10}$$

where M_n is the nominal flexural strength, M_s and M_f are the contribution of the steel reinforcement and the FRCM composite material to the nominal flexural strength, respectively. The strength reduction factor ϕ_m *is* given by Equation (11), as defined in ACI 318:

$$\phi_m = \begin{cases} 0.90 \ \text{ for } \varepsilon_t \geq 0.005 \\ 0.65 + \frac{0.25(\varepsilon_t - \varepsilon_{sy})}{0.005 - \varepsilon_{sy}} & \text{for } \varepsilon_{sy} < \varepsilon_t < 0.005 \\ 0.65 \ \text{ for } \ \varepsilon_t < \varepsilon_{sy} \end{cases} \tag{11}$$

where ε_t is the net tensile strain in extreme tension steel reinforcement at nominal strength, and ε_{sy} is the steel tensile yield strain.

8.3.1.1 Limitations: To limit the total force per unit width transferred to the concrete, the increment in flexural strength provided by the FRCM reinforcement shall not exceed 50 percent of the capacity of the structure without strengthening.

8.3.1.2 Serviceability: The tensile stress in the steel reinforcement under service load, f_{ss}, shall be limited to 80 percent of the steel yield strength, f_y, as indicated in Equation (12).

$$f_{ss} \leq 0.80\ f_y \tag{12}$$

8.3.1.3 Creep-rupture and Fatigue Stress Limits: The tensile stress levels in the FRCM reinforcement under service load, f_{fs}, shall be limited to the values shown in Table 3.

8.3.2 Axial Load Capacity Enhancement: The FRCM composite material may be applied to external surfaces of rectangular and circular reinforced concrete compression members to enhance the axial load capacity.

The stress-strain for FRCM-confined concrete is illustrated in Figure 2 and shall be determined using the following expressions:

$$f_c = \begin{cases} E_c\varepsilon_c - \dfrac{(E_c - E_2)^2}{4f'_c}(\varepsilon_c)^2 & 0 \leq \varepsilon_c \leq \varepsilon'_t \\ f'_c + E_2\varepsilon_c & \varepsilon'_t \leq \varepsilon_c \leq \varepsilon_{ccu} \end{cases} \tag{13}$$

$$\varepsilon'_t = \frac{2f'_c}{E_c - E_2} \tag{14}$$

$$E_2 = \frac{f'_{cc} - f'_c}{\varepsilon_{ccu}} \tag{15}$$

where E_c is the modulus of elasticity of concrete, E_2 is the slope of linear portion of stress-strain model for FRCM-confined concrete, f_c is the compressive stress in concrete, f'_c is the specified compressive strength of concrete, f'_{cc} is the maximum compressive strength of confined concrete, ε_c is the compressive strain level in the concrete, ε_{ccu} is the ultimate compressive strain of confined concrete, and ε'_t is the transition strain in the stress-strain curve of FRCM-confined concrete. ε_{ccu} corresponds to $0.85f'_{cc}$ in a lightly confined member (member confined to restore its concrete design compressive strength), or to the ultimate axial compressive strain of confined concrete corresponding to failure in a heavily confined member.

The maximum confined concrete compressive strength, f'_{cc}, and the maximum confinement pressure, f_l, shall be calculated using Equations (16), (17a) and (17b):

$$f'_{cc} = f'_c + \Psi_f\ 3.3\ \kappa_a\ f_l \tag{16}$$

$f_l = (2nA_fE_f\varepsilon_{fe})/D$ for circular cross section (17a)

$f_l = (2nA_fE_f\varepsilon_{fe})/(b^2+h^2)^{1/2}$ for rectangular cross section(17b)

where A_f is the area of grid reinforcement by unit width, n is the number of layers of grid reinforcement, D is the diameter of the compression member with circular cross section, and b and h are the short and the long side dimensions of the compression member with rectangular cross section, respectively. The additional strength reduction factor, Ψ_f, shall be taken equal to 0.95. The efficiency factor, κ_a, shall be calculated using Equation (20). The effective compressive strain level in the FRCM, ε_{fe}, shall be given by:

$$\varepsilon_{fe} = 0.55\ \varepsilon_{fu} \tag{18}$$

The minimum confinement ratio f_l/f'_c shall not be less than 0.08.

The contribution of the mortar to the compressive strength of the FRCM-confined compression member shall be neglected.

The ultimate axial compressive strain of confined concrete, ε_{ccu}, shall not exceed 0.01 to prevent excessive cracking and the resulting loss of concrete integrity. ε_{ccu} shall be calculated using the following stress-strain relationship:

$$\varepsilon_{ccu} = \varepsilon'_c\left(1.5 + 12\kappa_b\frac{f_l}{f'_c}\left(\frac{\varepsilon_{fe}}{\varepsilon'_c}\right)^{0.45}\right) \leq 0.01 \tag{19}$$

where ε'_c is the compressive strain of unconfined concrete corresponding to f'_c. The efficiency factor, κ_b, shall be calculated using Equation (21).

Based on the limitation set by Equation (19), f'_{cc} shall not exceed the value of the stress corresponding to ε_{ccu} equal to 0.01.

8.3.2.1 Circular Sections: For circular cross-sections, the shape factors κ_a and κ_b in Equations (16) and (19), respectively, shall be taken as 1.0.

8.3.2.2 Rectangular Sections: Rectangular sections where the ratio of longer to shorter section side dimension is not greater than 2.0, may have axial compression capacity enhanced by the confining effect of FRCM material placed with fiber strands running essentially perpendicular to the members' axis. For rectangular cross-sections, the shape factors κ_a in Equation (16) and κ_b in Equation (19) shall be calculated using Equations (20) and (21), respectively (Figure 3).

$$\kappa_a = \frac{A_e}{A_c}\left(\frac{b}{h}\right)^2 \qquad (20)$$

$$\kappa_b = \frac{A_e}{A_c}\left(\frac{h}{b}\right)^{0.5} \qquad (21)$$

where,

$$\frac{A_e}{A_c} = \frac{1-\left(\left(b/h\right)\left(h-2r\right)^2+\left(h/b\right)\left(b-2r\right)^2\right)\Big/\left(3A_g\right)-\rho_g}{1-\rho_g} \qquad (22)$$

In Equation (22), A_c is the net cross-sectional area of the compression member, A_e is the area of the effectively confined concrete, A_g is the gross cross-sectional area of the compression member, ρ_g is the ratio of the area of longitudinal steel reinforcement, A_s, to the gross cross-sectional area of the compression member.

The cross-section corners must be rounded to a radius, r, not less than $^3/_4$ inch (20 mm), before placing FRCM material. For rectangular sections within aspect ratio h/b > 2.0, the effectiveness of the confinement shall be subject to special analysis confirmed by test results.

8.3.3 Ductility Enhancement: The FRCM composite material oriented essentially transversely to the members' axis may be used to enhance flexural ductility capacity of circular and rectangular sections where the ratio of longer to shorter section dimension does not exceed 2.0. The enhancement is provided by increasing the effective ultimate compression strain of the section as computed in Equation (19).

8.3.4 Shear Strength Enhancement of Concrete Elements: The FRCM composite material bonded to surfaces of reinforced concrete members with the fiber strands oriented essentially perpendicular to the members' axis may be used to enhance the design shear strength by acting as external shear reinforcement. Shear strengthening using external FRCM may be provided at locations of expected plastic hinges or stress reversal and for enhancing post-yield flexural behavior of members in moment frames resisting seismic loads only by completely wrapping the section. Only continuous FRCM U-wraps or continuous complete wraps shall be considered.

The design tensile strain in the FRCM shear reinforcement, ε_{fv}, shall be calculated by Equation (23):

$$\varepsilon_{fv} = \kappa_v\, \varepsilon_{fu} \leq 0.004 \qquad (23)$$

The bond-reduction coefficient, κ_v, shall be taken as 0.4.

The design tensile strength of the FRCM shear reinforcement, f_{fv}, shall be calculated in accordance with Equation (24):

$$f_{fv} = 0.85\, E_f\, \varepsilon_{fv} \qquad (24)$$

Fiber strands shall be oriented perpendicular to the axis of the member and shall not have a misalignment of more than 5 degrees.

The design shear strength shall be calculated in accordance with Equation (25).

$$\phi_v\, V_n = \phi_v\,(V_c + V_s + V_f) \qquad (25)$$

where V_n is the nominal shear strength; V_c, V_s, and V_f are the contribution of the concrete, the steel reinforcement and the FRCM composite material to the nominal shear strength, respectively. The strength reduction factor ϕ_v shall be equal to 0.75 as per ACI 318. V_c and V_s are calculated according to ACI 318. The shear contribution of the FRCM shear reinforcement, V_f, shall be given by Equation (26)

$$V_f = n\, A_f\, f_{fv}\, d \qquad (26)$$

where n is the number of layers of grid reinforcement, A_f is area of grid reinforcement by unit width effective in shear, and d is the distance from extreme compression fiber to centroid of tension reinforcement. The total shear strength provided by FRCM and steel reinforcement shall be limited to the following:

$$V_s + V_f \leq 8\sqrt{f_c'}\,b_w d \qquad (27)$$

$$V_s + V_f \leq 0.66\sqrt{f_c'}\,b_w d \qquad \text{(SI Units)}$$

where b_w is the web width. For rectangular sections with shear enhancement provided by transverse FRCM composite material, section corners must be rounded to a radius not less than $^3/_4$ inch (20 mm) before placement of the FRCM material.

8.3.4.1 Limitations: To limit the total force per unit width transferred to the concrete, the increment in shear strength provided by the FRCM reinforcement shall not exceed 50% of the original capacity.

9.0 EVALUATION REPORT RECOGNITION

The evaluation report shall include the following:

9.1 Basic information required by Section 2.0 of this criteria, including product description, installation procedures, packaging and identification information, and material properties as determined in Section 4.0 of this criteria.

9.2 A statement that design and installation must be in accordance with the published ICC-ES report, the approved quality documentation, the Design Manual, and the IBC.

9.3 A statement that copies of quality documentation and the Design Manual must be submitted to the code official for each project using the systems.

9.4 A statement that complete construction documents, including plans and calculations verifying compliance with this report, must be submitted to the code official for each project at the time of permit application. The construction documents must be prepared and sealed by a registered design professional where required by the statutes of the jurisdiction in which the project is to be constructed.

9.5 A statement that special inspection for jobsite application of the systems must be provided in accordance with Section 6.2 of this criteria.

9.6 If there is testing in accordance with Section 4.9 of this criteria, a statement about the effect of the FRCM system on the fire-resistance rating of the concrete or masonry structure. Otherwise, there must be a statement that the fire-resistance rating of the strengthened structure is outside the scope of the evaluation report.

9.7 If the system is tested in accordance with Section 4.10 of this criteria, a statement about the flame spread and smoke developed indices for the system.

10.0 NOMENCLATURE:

A_c = net cross-sectional area of the compression member, in.^{2} (mm^2)

A_e = area of the effectively confined concrete, in.^{2} (mm^2)

A_f = area of grid reinforcement by unit width, in.^{2}/in (mm^2/mm)

A_g = gross cross-sectional area of the compression member, in.^{2} (mm^2)

A_s = area of longitudinal steel reinforcement, in.^{2} (mm^2)

D = diameter of the compression member, in. (mm)

E_2 = slope of linear portion of stress-strain model for FRCM-confined concrete, psi (MPa)

E_c = modulus of elasticity of concrete, psi (MPa)

E_f = tensile modulus of elasticity of the cracked FRCM composite material specimen, psi (MPa)

H = height of the masonry wall, in. (mm)

L = length of the wall in the direction of the applied shear force, in. (mm)

M_f = contribution of the FRCM composite material to the nominal flexural strength, in-lb (N-mm)

M_m = contribution of the reinforced masonry to the nominal flexural strength, in-lb (N-mm)

M_n = nominal flexural strength, in-lb (N-mm)

M_s = contribution of the steel reinforcement to the nominal flexural strength, in-lb (N-mm)

V_c = contribution of the concrete to the nominal shear strength, lb (N)

V_f = contribution of the FRCM composite material to the nominal shear strength, lb (N)

V_m = contribution of the (unreinforced or reinforced) masonry to the nominal shear strength, lb (N)

V_n = nominal shear strength, lb (N)

V_s = contribution of the steel reinforcement to the nominal shear strength, lb (N)

b = short side dimension of the compression member with rectangular cross section, in. (mm)

b_w = web width, in. (mm)

d = distance from extreme compression fiber to centroid of tension reinforcement, in. (mm)

f_c = compressive stress in concrete, psi (MPa)

f'_c = specified compressive strength of concrete, psi (MPa)

f'_{cc} = maximum compressive strength of confined concrete, psi (MPa)

f'_{co} = compressive strength of unconfined concrete; also equal to 0.85f'_c, psi (MPa)

f_{fe} = effective tensile stress level in FRCM composite material attained at failure, psi (MPa)

f_{fu} = ultimate tensile strength of the FRCM composite material, psi (MPa)

f_{fv} = design tensile strength of the FRCM shear reinforcement, psi (MPa)

f_{fs} = tensile stress in the FRCM reinforcement under service load, psi (MPa)

f_l = maximum confining pressure due to FRCM jacket, psi (MPa)

f_{ss} = tensile stress in the steel reinforcement under service load, psi (MPa)

f_y = steel tensile yield strength, psi (MPa)

h = long side dimension of the compression member with rectangular cross section, in. (mm)

n = number of layers of grid reinforcement

r = radius of the edges of a rectangular cross section confined with FRCM, in. (mm)

t = thickness of the masonry wall in. (mm)

ε_c = compressive strain level in the concrete, in./in. (mm/mm)

ε'_c = compressive strain of unconfined concrete corresponding to f'_c, in./in. (mm/mm); may be taken as 0.002

ε_{ccu} = ultimate compressive strain of confined concrete corresponding to 0.85f'_{cc} in a lightly confined member (member confined to restore its concrete design compressive strength), or ultimate compressive strain of confined concrete corresponding to failure in a heavily confined member

ε_{fd} = design tensile strain of the FRCM composite material, in./in. (mm/mm)

ε_{fe} = effective tensile strain level in FRCM composite material attained at failure, in./in. (mm/mm)

ε_{fv} = design tensile strain of the FRCM shear reinforcement, in./in. (mm/mm)

ε_{fu} = ultimate tensile strain of the FRCM composite material, in./in. (mm/mm)

ε_{sy} = steel tensile yield strain, in./in. (mm/mm)

ε_t = net tensile strain in extreme tension steel reinforcement at nominal strength, in./in. (mm/mm)

ε'_t = transition strain in the stress-strain curve of FRCM-confined concrete, in./in. (mm/mm)

ϕ_m = strength reduction factor for flexure

ϕ_v = strength reduction factor for shear

K_a = efficiency factor for FRCM reinforcement in the determination of f'_{cc} (based on the geometry of the cross section)

K_b = efficiency factor for FRCM reinforcement in the determination of ε_{ccu} (based on the geometry of cross section)

K_v = bond-reduction coefficient for shear

μ = displacement ductility level, defined relative to yield or cracking displacement.

Ψ_f = additional strength reduction factor for FRCM confined concrete

ρ_g = ratio of the area of longitudinal steel reinforcement to the cross-sectional area of a compression member (A_s/bh).■

TABLE 1—SUMMARY OF MATERIAL TESTS REQUIRED FOR EACH FRCM SYSTEM[1]

GRID	CONDITIONING	TEST TYPE	HOURS	NUMBER OF REPLICATES	AC 434 SECTIONS		
Continuous		Dry shrinkage		5	4.2.1		
		Void content		5	4.2.2		
			total	***10***			
Continuous	Ambient	Direct tension		5	4.2.3	4.4	
	Freeze/thaw			5			
	Ambient	Inter. shear		5	4.2.4		
	Freeze/thaw			5			
			total	***20***			
Continuous	Ambient	Direct tension	1,000	5	4.2.3	4.5	
	Water			5			
	Saltwater			5			
	Alkali			5			
	Ambient		3,000	5			
	Water			5			
	Saltwater			5			
	Alkali			5			
	Ambient	Inter. shear	1,000	5	4.2.4		
	Water			5			
	Saltwater			5			
	Alkali			5			
	Ambient		3,000	5			
	Water			5			
	Saltwater			5			
	Alkali			5			
			total	***80***			
Continuous	Ambient	Direct tension		5	4.2.3	4.6	
	Fuel			5			
			total	***10***			
Lap	Ambient	Direct tension	1,000	5	4.2.3	4.5	4.7
	Water			5			
	Saltwater			5			
	Alkali			5			
	Ambient		3,000	5			
	Water			5			
	Saltwater			5			
	Alkali			5			
			total	***40***			
Continuous	Ambient	bond	1,000	5	4.8		
	Water			5			
	Saltwater			5			
	Alkali			5			
	Ambient		3,000	5			
	Water			5			
	Saltwater			5			
	Alkali			5			
			total	***40***			

[1] See Section 4.0 of this criteria for details.

TABLE 2—ENVIRONMENTAL DURABILITY TESTS

ENVIRONMENTAL DURABILITY TEST	RELEVANT SPECIFICATION	TEST CONDITION	TEST DURATION	PERCENT RETENTION	
				Hours	
				1,000	3,000
Water resistance	ASTM D 2247 ASTM E 104	100%, 100 ± 2°F	1,000 and 3,000 hours	85	80
Saltwater resistance	ASTM D 1141 ASTM C 581	Immersion at 73 ± 2°F			
Alkali resistance		Immersion in solution with pH = 9.5 or higher and 73 ± 3°F			

TABLE 3—CREEP RUPTURE STRESS LIMITS FOR REINFORCEMENT BASED ON FIBER TYPE

PARAMETER	FIBER TYPE			
	AR Glass	Aramid	Carbon	PBO
Creep rupture	$0.20f_u$	$0.30f_u$	$0.55f_u$	$0.30f_u$

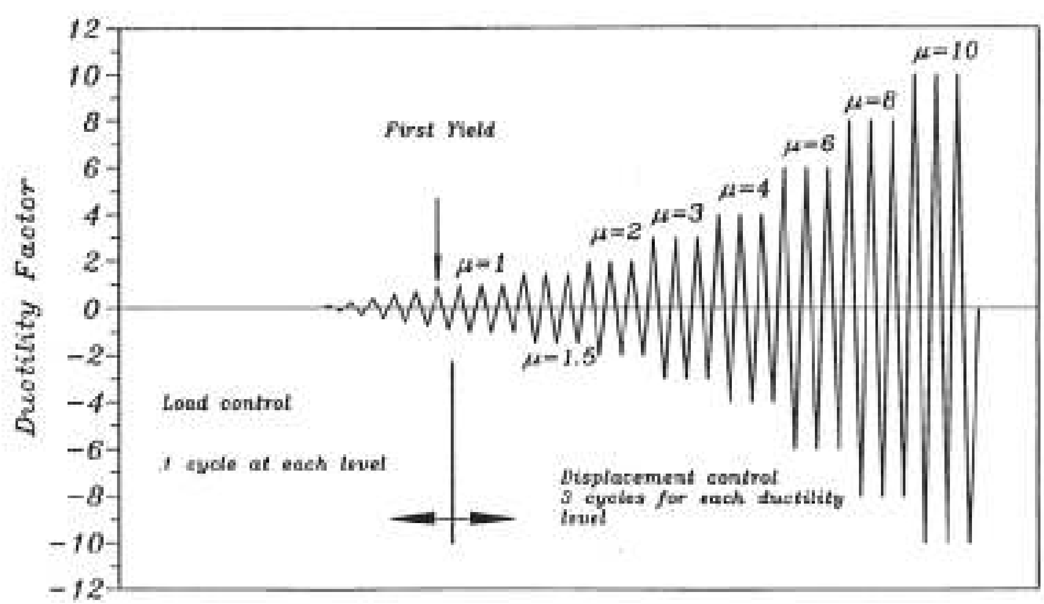

FIGURE 1—TEST SEQUENCE OF IMPOSED DISPLACEMENT

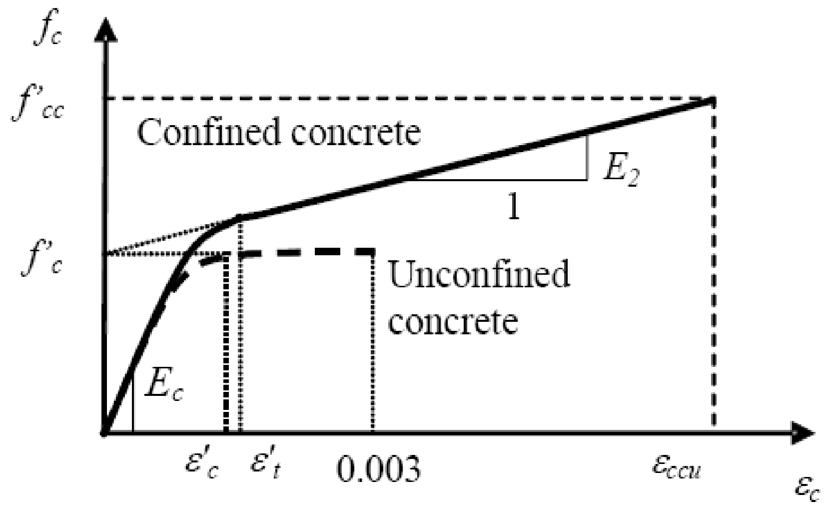

FIGURE 2—STRESS-STRAIN DIAGRAM FOR FRP-CONFINED CONCRETE

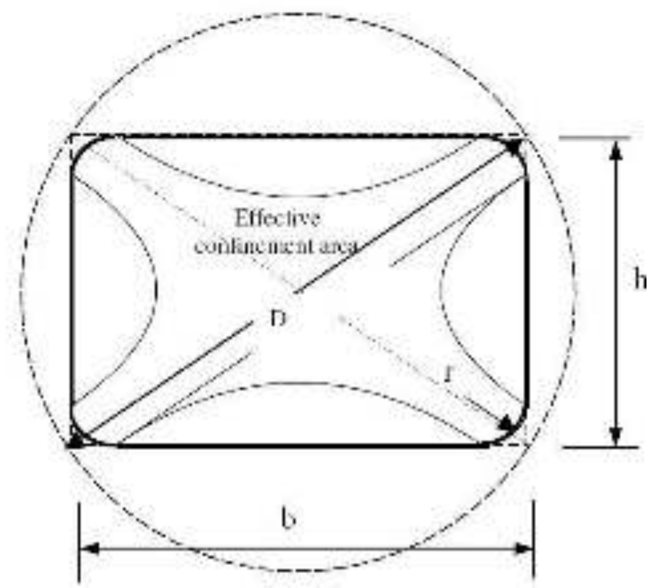

FIGURE 3—EQUIVALENT CIRCULAR CROSS SECTION

Annex A

Tensile Testing of Fiber-reinforced Cementitious Matrix (FRCM) Composite Specimens

A1.0 Summary of Test Method

A thin flat strip of material having a near-constant rectangular cross section is mounted in the grips of a mechanical testing machine and loaded with monotonically increasing load in tension while recording load and movement. The ultimate strength of the material can be determined from a maximum load carried before failure. The coupon strain or elongation is monitored with displacement transducers to determine the nominal stress-strain response of the material, and from that the cracking stress and strain, ultimate tensile strain, tensile modulus of elasticity before and after cracking of cement-based matrix can be derived.

This test procedure is designed to produce tensile property data for material specifications, quality assurance, and structural design and analysis. Factors that influence the tensile response and shall therefore be reported include the following: material, methods of material preparation and lay-up, specimen preparation, specimen conditioning, environment of testing, specimen alignment and gripping, and speed of testing. Properties, in the test direction, which may be obtained from this test include:

1. Ultimate tensile strength
2. Ultimate tensile strain
3. Tensile modulus of elasticity of uncracked specimen
4. Tensile modulus of elasticity of cracked specimen
5. Transition point

Attention shall be paid to material and specimen preparation, gripping, and test system alignment. Poor material fabrication practices, lack of control in alignment of fiber grid, and damage induced by improper cutting and machining the coupons are known causes of high material data scatter. Specimen gripping problems can also cause a high percentage of grip-influenced failures and therefore more scatter in data. Every effort shall be made to eliminate excess bending due to system misalignment and out-of-tolerance conditions caused by poor specimen preparation.

A2.0 Apparatus

A2.1 Dimension Measurements: The accuracy of instruments used for measuring dimensions of the test specimens shall be suitable for reading to within 1 percent of the sample dimensions.

A2.2 Testing Machine: The testing machine shall be in conformance with Practices ASTM E 4. The testing machine shall have both an essentially stationary head and a movable head. The drive mechanism shall be capable of imparting to the movable head a controlled velocity with respect to the stationary head. The testing machine load sensing device shall be able to indicate the applied load to the specimen within 1 percent of the indicated value. Each head of the testing machine shall carry one grip for holding the test specimen in coincident with the longitudinal axis of the specimen. The grips shall apply sufficient lateral pressure to prevent slippage between the grip face and the coupon. It is desirable to use grips that are rotationally self-aligning to minimize bending stresses in the coupon.

A.2.3 Strain Indicating Device: An extensometer satisfying Practice ASTM E 83, Class B-1 requirements can be used for strain/elongation measurement. A minimum gage length of 2 inches (50 mm) shall be used. Since the coupon undergoes cracking in the early stages of loading, the gage length shall be adequate to at least include within itself one transverse crack. The bearing points of the extensometer on the coupon shall not be disturbed by cracking. If cracking occurs at the bearing points, the specimen shall be unloaded and extensometer moved. The discontinuity in elongation reading can be removed in data reduction process by matching the stop and restart point or similar means. The weight of extensometer shall not cause significant bending in the specimen.

A3.0 Test Specimens

At least five specimens shall be tested per test condition. Specimens can be cut from larger panels laid up in special molds. Control of fiber grid alignment is critical in lay-up procedure. Effective cutting tools and methods need to used, and precautions shall be taken to avoid notches, undercuts, uneven surfaces, or delaminations. The specimen preparation method shall be reported. Specimens shall be labeled properly to be distinct from each other and traceable to the raw material.

The test specimens shall be rectangular coupons. The thickness of coupons shall be as required and be a function of number of layers and thickness of matrix for each layer. The width of the coupon shall be adequate to include a minimum number of strands (e.g., three3 strands in each layer) and shall not be less than four times the thickness of the specimen. The width shall also be kept as a multiple of the grid spacing. Also, in case the strands in different layers are staggered with respect to each other, it is preferable to have the same number of strands in each layer along the width of the coupon. The minimum length of the coupon shall include gripping distance, plus twice the width plus gage length. Longer lengths are preferred to minimize the bending effects on the specimen.

Metallic tabs (e.g., steel, aluminum) are recommended for gripping to avoid damage to the specimen by grips. The tabs can be glued to the specimen ends (two at each end, one at each face). The tabs shall have the same width as the coupon. The tab length can be calculated based on the maximum expected tensile load, glue and tab bond strength to the matrix, and development length of the fiber strands within matrix. A minimum of 3 inches (75 mm) tab length is recommended. The thickness of the tabs shall be adequate to distribute uniformly the gripping force to the overall width of the coupons. A minimum thickness of $^{1}/_{16}$ inch (2 mm) is recommended.

A4.0 Calibration

The accuracy of all measuring equipment shall have certified calibrations that are current at the time of use of the equipment.

A5.0 Conditioning

Unless a different environment is specified as part of the experiment, test specimens shall be moist cured at least for seven days after lay-up, and another seven days at laboratory environment before testing. Tests can be conducted at 14-day age and later. Storage after curing and testing shall be at standard laboratory atmospheric conditions.

A6.0 Procedure

After conditioning and before testing, coupon type and geometry and environmental conditioning test parameters are specified. The overall cross-sectional area of the specimen is calculated as follows:

$$A = w_s h_s \tag{A1}$$

where w_s is the nominal width and h_s is the nominal thickness of the coupon. The width and thickness are measured at three locations along the specimen and averaged. This value is determined for reporting purposes only. For computation of FRCM mechanical properties, the area of grid reinforcement by unit width, A_f measured in.^{2}/in (mm^2/mm), as reported by the manufacturer, is used.

Special tabs prepared for installation are glued to the specimen. The glue shall be permitted to cure per applicant instruction. The specimen placed in the grips of testing machine, taking care to align the axis of the gripped specimen with the test direction. If applicable, the grips are tightened. An initial minimal tension, less than 5 percent of the anticipated failure load, is applied to straighten potential bow in the specimen. The displacement transducer is attached to the specimen, preferably symmetrically about the mid-span, mid-width location. The load is applied under displacement control. The loading rate can be adjusted by the velocity of the machine head. A standard rate of 0.01 in./min (0.2 mm/min) is recommended.

The load versus displacement shall be recorded continuously or at frequent regular intervals. The load, displacement, and mode of cracking (or any other damage) during testing that would cause transition region in otherwise a linear response are recorded. Cracks may occur at regular spacing along the specimen. If the cracks intercept the transducer bearing points, the specimen shall be unloaded to the level of the initial loading. The displacement transducer shall then be slightly moved and reinstalled to bear at uncracked region of the matrix. Reload the specimen with the same rate of loading and continue data recording. The displacement transducer shall be removed before anticipated failure to avoid damage to the sensor, but load readings shall continue until failure. The maximum load, the failure load, and corresponding displacements at, or as near as possible to, the moment of rupture shall be recorded, along with the failure mode and location.

A7.0 Calculation

The recorded data shall be reduced to reflect the initial tensile loading and reading discontinuity if the transducer were to be moved during the test. This will likely result in a near bilinear response curve (Figure A1) with an initial line for uncracked specimen, a secondary line for cracked specimen, and possibly a curved transition segment in between.

A7.1 Expected Tensile Stress – Strain Curve: The expected tensile stress, f_f, versus tensile strain, ε_f, curve of an FRCM coupon specimen is shown in Figure A1. If a curved segment exist in between two linear portions of the response curve, the two lines to initial and secondary segments of the response curve shall be continued until they intersect. The displacement and load corresponding to the intersection are calculated as the transition point data, named T in Figure A1.

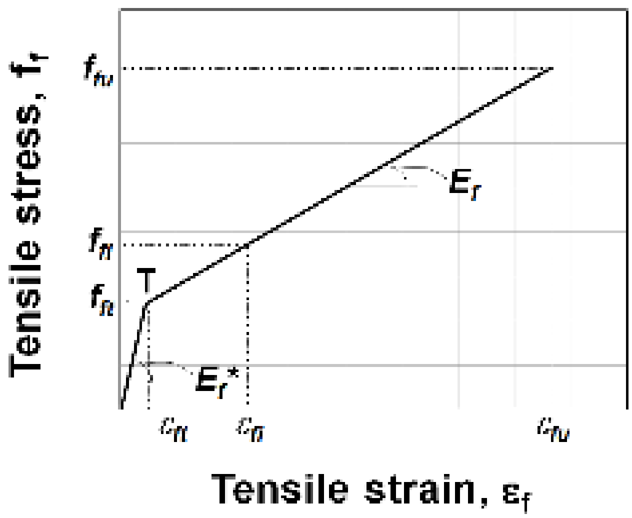

FIGURE A1—EXPECTED TENSILE STRESS VERSUS TENSILE STRAIN CURVE OF AN FRCM COUPON SPECIMEN. THE TRANSITION POINT T IS INDICATED

In Figure A1 the following quantities are shown:

E_f = tensile modulus of elasticity of the cracked specimen, psi (MPa)

E_f^* = tensile modulus of elasticity of the uncracked specimen, psi (MPa)

f_{fi} = tensile stress at *i*th data point, psi (MPa)

f_{fu} = ultimate tensile strength, psi (MPa)

f_{ft} = tensile stress corresponding to the transition point, psi (MPa)

ε_{fi} = tensile strain at *i*th data point, in./in. (mm/mm)

ε_{fu} = ultimate tensile strain, in./in. (mm/mm)

ε_{ft} = tensile strain corresponding to the transition point, in./in. (mm/mm)

A7.2 Transition Point (T): If a curved segment exist in between two linear portions of the response curve, the two lines to initial and secondary segments of the response curve shall be continued until they intersect. The displacement and load corresponding to the intersection are calculated as the transition point data.

A7.3 Tensile Stress/Tensile Strength: The ultimate tensile strength and, if needed, the tensile stress at a specific data point are calculated using the following equations:

$$f_{fu} = P_{max} / (A_f\, w_s) \tag{A2}$$

$$f_{fi} = P_i / (A_f\, w_s) \tag{A3}$$

where:

P_{max} = maximum load before failure, lbf (N).

P_i = load at *i*th data point, lbf (N).

A_f = area of grid reinforcement by unit width, in.^{2}/in (mm^2/mm)

w_s = nominal width of the specimen , in. (mm)

A7.4 Tensile Strain: Tensile strain at a specific data point is calculated using the following equation:

$$\varepsilon_{fi} = \delta_i / L_g \tag{A4}$$

where:

δ_i = extensometer displacement at *i*th data point, in. (mm).

L_g = extensometer gage length, in. (mm).

A7.5 Tensile Modulus of Elasticity of Uncracked Specimen: On the linear segment of the initial line of the response bilinear curve corresponding to uncracked behavior of the specimen two points connecting the results in a line that closely follows the trend and slope of the response curve at that region are selected. The tensile modulus of elasticity of the uncracked specimen is calculated using:

$$E_f^* = \Delta f / \Delta \varepsilon \tag{A5}$$

where:

Δf = difference in tensile stress between two selected points, psi (MPa).

$\Delta\varepsilon$ = difference in tensile strain between two selected points, in/in (mm/mm).

Alternatively, the slope of the initial line passing through the origin and drawn to obtain the transition point on the response curve can be calculated as the modulus of elasticity of uncracked specimen.

A7.6 Tensile Modulus of Elasticity of Cracked Specimen: On the linear segment of the secondary line of the response bilinear curve corresponding to cracked behavior of the specimen two points connecting the results in a line that closely follows the trend and slope of the response curve at that region are selected. The tensile modulus of elasticity of the cracked specimen is calculated using:

$$E_f = \Delta f / \Delta\varepsilon \tag{A6}$$

Alternatively, the slope of the secondary line drawn to obtain the transition point on the response curve can be calculated as the modulus of elasticity of cracked specimen.

A7.7 Ultimate Tensile Strain: Ultimate tensile strain, ε_{fu}, is calculated by extrapolating the secondary line in the bilinear response curve, or using the following equation:

$$\varepsilon_{fu} = \varepsilon_{ft} + (f_{fu} - f_{ft}) / E_f \tag{A7}$$

A8.0 Report

The following information shall be reported to the maximum extent applicable:

- Date and location of the test
- Name of test operator
- Any variations to this test method
- Identification of the material tested including material specification, type, and designation, manufacturer
- Description of the fabrication steps used to prepare the composite material including fabrication date, process, cure cycle, and description of equipment used
- Orientation of the fiber grid
- Area of grid reinforcement by unit width and nominal cross-section area of all specimens
- Method of preparation of test specimen including labeling system, geometry, sampling method, cutting, tab identification, geometry and adhesive used
- Calibration information for all measurement and test equipment
- Description of the test machine
- Conditioning parameters and results
- Temperature and humidity of testing laboratory
- Number of specimens tested
- Speed of testing
- Type and placement of transducers on the test specimens
- Stress-strain curve and tabulated results
- Individual strengths, average, standard deviation, and coefficient of variation (in percent) for the population
- Individual strains at failure and average, standard deviation, and coefficient of variation (in percent) for population
- Strains used for modulus calculation
- Describe the method used for calculation of the moduli of elasticity
- Individual moduli of elasticity and average, standard deviation, and coefficient of variation (in percent) for population
- If transition strain is determined, describe the method of linear fit
- Individual values of transition strains and average, standard deviation, and coefficient of variation (in percent) for population
- Failure mode and location of failure for each specimen.