



# ACCEPTANCE CRITERIA FOR CONCRETE AND REINFORCED AND UNREINFORCED MASONRY STRENGTHENING USING EXTERNALLY BONDED FIBER-REINFORCED POLYMER (FRP) COMPOSITE SYSTEMS

**AC125**

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## PREFACE

Evaluation reports issued by ICC Evaluation Service, Inc. (ICC-ES), are based upon performance features of the International family of codes and other widely adopted code families, including the Uniform Codes, the BOCA National Codes, and the SBCCI Standard Codes. Section 104.11 of the *International Building Code*<sup>®</sup> 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.

Similar provisions are contained in the Uniform Codes, the National Codes, and the Standard Codes.

This acceptance criteria has been issued to provide all interested parties with guidelines for demonstrating compliance with performance features of the applicable code(s) referenced in the acceptance criteria. The criteria was developed and adopted following public hearings conducted by the ICC-ES Evaluation Committee, and is effective on the date shown above. All reports issued or reissued on or after the effective date must comply with this criteria, while reports issued prior to this date may be in compliance with this criteria or with the previous edition. If the criteria is an updated version from the previous edition, a solid vertical line (|) in the margin within the criteria indicates a technical change, addition, or deletion from the previous edition. A deletion indicator (→) is provided in the margin where a paragraph has been deleted if the deletion involved a technical change. This criteria may be further revised as the need dictates.

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# ACCEPTANCE CRITERIA FOR CONCRETE AND REINFORCED AND UNREINFORCED MASONRY STRENGTHENING USING EXTERNALLY BONDED FIBER-REINFORCED POLYMER (FRP) COMPOSITE SYSTEMS

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## 1.0 INTRODUCTION

**1.1 Purpose:** The purpose of this criteria is to establish minimum requirements for the issuance of ICC Evaluation Service, Inc. (ICC-ES), evaluation reports on fiber-reinforced polymer (FRP) composite systems under the 2006 *International Building Code*<sup>®</sup> (IBC) and the 1997 *Uniform Building Code*<sup>™</sup> (UBC). Bases of recognition are

IBC Section 104.11 and UBC Section 104.2.8.

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

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**1.2 Scope:** This acceptance criteria applies to passive FRP composite systems used to strengthen existing concrete and masonry structural elements. Properties evaluated include flexural, and shear capacities, performance under environmental exposures, performance under exposure to fire conditions, and structural design procedures.

### 1.3 Referenced Documents:

**1.3.1** 2006 *International Building Code*<sup>®</sup> (IBC), International Code Council.

**1.3.2** 1997 *Uniform Building Code*<sup>™</sup> (UBC), International Conference of Building Officials.

**1.3.3** ICC-ES Acceptance Criteria for Inspection and Verification of Concrete and Reinforced and Unreinforced Masonry Strengthening Using Fiber-reinforced Polymer (FRP) Composite Systems (AC178).

**1.3.4** ASTM C 297-94, Test Method for Tensile Strength of Flat Sandwich Constructions in Flatwise Plane, ASTM International.

**1.3.5** ASTM C 581-94, Practice for Determining the Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service, ASTM International.

**1.3.6** ASTM D 696-91, Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between -30°C and 30°C with a Vitreous Silica Dilatometer, ASTM International.

**1.3.7** ASTM D 1141-91, Practice for Preparation of Substitute Ocean Water, ASTM International.

**1.3.8** ASTM D 2247-97, Practice for Testing Water Resistance of Coatings in 100% Relative Humidity, ASTM International.

**1.3.9** ASTM D 2344-84 (1995), Test Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method, ASTM International.

**1.3.10** ASTM D 2584-94, Test Method for Ignition Loss of Cured Reinforced Resins, ASTM International.

**1.3.11** ASTM D 2990-95, Test Methods for Tensile, Compressive, and Flexural Creep and Creep Rupture of Plastics, ASTM International.

**1.3.12** ASTM D 3029-94, Standard Test Methods for Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Tup (Falling Weight), ASTM International.

**1.3.13** ASTM D 3039-00<sup>e2</sup>, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM International.

**1.3.14** ASTM D 3045-92, Standard Practice for Heat Aging of Plastics Without Load, ASTM International.

**1.3.15** ASTM D 3083-89, Specification for Flexible Poly (Vinyl Chloride) Plastic Sheeting for Pond, Canal, and Reservoir Lining, ASTM International.

**1.3.16** ASTM D 3165-95, Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies, ASTM International.

**1.3.17** ASTM D 3171-95, Standard Test Method for Constituent Content of Composite Materials, ASTM International.

**1.3.18** ASTM D 4065-95, Standard Practice for Determining and Reporting Dynamic Mechanical Properties of Plastics, ASTM International.

**1.3.19** ASTM D 4541-02, Standard Test Method for Pull-off Strength of Coatings Using Portable Adhesion Testers, ASTM International.

**1.3.20** ASTM E 104-85 (1996), Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions, ASTM International.

**1.3.21** ASTM E 831-00, Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis, ASTM International.

**1.3.22** ASTM E 1142-97, Standard Terminology Relating to Thermophysical Properties, ASTM International.

**1.3.23** ASTM G 153-04 Standard Practice for Operating Enclosed Carbon Arc Light Apparatus for Exposure of Nonmetallic Materials, ASTM International.

**1.3.24** NSF 61-2003e, Drinking Water Components—Health Effects, NSF International.

## 2.0 DEFINITIONS

**2.1 Design Values:** The FRP composite material's load and deformation design capacities, that are based on either working stress or ultimate strength methods.

**2.2 Composite Material:** A combination of high-strength fibers and polymer matrix material. This FRP composite may be applied either during manufacture of the structural element or at the project location.

**2.3 Cracking Load and Displacement:** Load and displacement at which the moment-curvature relationship of the concrete or masonry section first changes slope or at which the cracking moment is reached.

**2.4 Yielding Load and Displacement:** Load and displacement at which longitudinal steel reinforcement of the concrete or masonry section first yields.

**2.5 Passive and Active Composite Systems:** Active systems are those FRP composite systems where the FRP composite materials are post-tensioned after installation by means such as pressure injection between the composite material and the concrete or masonry section. Passive systems are not post-tensioned after installation.

## 3.0 REQUIRED INFORMATION

**3.1 Description:** A detailed description of the strengthening system is needed, including the following items:

1. Description and identification of the product or system. Identification shall include the ICC-ES evaluation report number.

2. Restrictions or limitations on use.

**3.2 Installation Instructions:** Instructions shall include the following items.

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

**3.3 Structural Design:** The structural applications of the system shall address the following items:

1. Clarification of recognition under either Chapter 19 or Chapter 21 of the IBC or UBC.
2. Complete description of details.
3. Details on how the product or system does or does not comply with Chapter 19 of the IBC or UBC, including conformities and deviations. Details should include positive statements that the product or system does comply with Chapter 19 or 21 of the IBC or UBC in the following areas . . . ; and negative statements that it does not comply in the following areas. . . .
4. Details and examples of how the product or system is designed and analyzed, including formulas, with procedures and properties needed for design and analysis. The engineering analysis should define failure modes or force and deflection limit states.
5. Use of anchors shall be considered where the FRP composite material bond to substrate is critical.

### 4.0 TESTING LABORATORIES AND REPORTS OF TESTS

- 4.1 Testing laboratories shall comply with Section 2.0 of the ICC-ES Acceptance Criteria for Test Reports (AC85) and Section 4.2 of the ICC-ES Rules of Procedure for Evaluation Reports.
- 4.2 Test reports shall comply with AC85.
- 4.3 **Product Sampling:** Products shall be sampled in accordance with Section 3.1 of AC85.

### 5.0 QUALIFICATION TESTS

**5.1 Qualification Test Plan:** The intent of testing is to verify the design equations and assumptions used in the engineering analysis. All or part of the tests described in this section, and any additional tests identified for special features of the product or system, shall be specified. The test plan shall be a complete document.

Overall, qualification testing must provide data on material properties, force and deformation limit states, and failure modes, to support a rational analysis procedure. The specimens shall be constructed under conditions specified by the manufacturer, including curing. Tests must simulate the anticipated loading conditions, load levels, deflections, and ductilities.

#### 5.2 Columns:

##### 5.2.1 Flexural Tests:

**5.2.1.1 Configuration:** Column specimens shall be configured to induce flexural limit states or failure modes.

Either cantilever or double fixity (reverse curvature) is permitted in specimens. Extremes of dimensional, reinforcing, and strength parameters shall be considered.

**5.2.1.2 Procedure:** For seismic or wind-load applications, the lateral load procedure shall conform to Figure 1. For gravity (nondynamic) 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 material properties and an extreme concrete or masonry fiber compression strain of 0.003.

#### 5.2.2 Shear Tests:

**5.2.2.1 Configuration:** Column specimen spans shall be configured to induce shear limit states or failure modes. Double fixity (reverse curvature) is required. Extremes of dimensional, reinforcing, and compressive strength parameters shall be considered.

**5.2.2.2 Procedure:** For seismic or wind-load application, the lateral load procedure shall conform to Figure 1. For gravity (nondynamic) 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 material properties.

#### 5.3 Beam-to-Column Joints:

**5.3.1 Configuration:** The beam-to-column joint shall be configured to induce joint-related limit states or failure modes. The column portion may be constructed to represent a section between inflection points. Extremes of dimensional, reinforcing and compressive strength parameters shall be considered.

**5.3.2 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 material properties.

#### 5.4 Beams:

##### 5.4.1 Flexural Tests:

**5.4.1.1 Configuration:** Beam spans shall be configured to induce flexural limit states or failure modes. Either simple or rigid supports are permitted. Extremes of dimensional, reinforcing, and compressive strength parameters shall be considered.

**5.4.1.2 Procedure:** For seismic or wind-load application, the lateral load procedure shall conform to Figure 1. For gravity (nondynamic) loading application, the load may be monotonically applied. The limit states shall be determined based on material properties and an extreme concrete or masonry fiber compression strain of 0.003.

##### 5.4.2 Shear Tests:

**5.4.2.1 Configuration:** Beam spans shall be configured to induce shear limit states or failure modes. Either simple or rigid supports are permitted. Extremes of dimensional, reinforcing, and compressive strength parameters shall be considered.

**5.4.2.2 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 material properties.

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### 5.5 Walls:

#### 5.5.1 Wall Flexural Tests (Out-of-Plane Load):

**5.5.1.1 Configuration:** Wall flexural specimens shall be configured to induce out-of-plane flexural limit states and failure modes. Extremes of dimensional, reinforcing, and compressive strength parameters shall be considered.

**5.5.1.2 Procedure:** 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 air-bags or by other means representing actual conditions. The lateral load procedure consists of:

**5.5.1.2.1** Load specimens in both directions, to find cracking and yielding load and deformation at first cracking. For unreinforced masonry, only cracking load and deformation are required.

**5.5.1.2.2** At least two cycles of loading in both directions under displacement control at each deformation level. The deformation levels shall consist of multiples of the deformation at yielding for reinforced concrete or masonry sections or cracking for unreinforced masonry sections.

**5.5.1.2.3** The specimens are loaded in both directions until the strengthening system is damaged, its capacity is reached, or desired limit states are achieved.

#### 5.5.2 Wall Shear Tests (In-Plane Shear):

**5.5.2.1 Configuration:** Wall specimens shall be configured to induce in-plane shear limit states or failure modes. Extremes of dimensional, reinforcing and compressive strength parameters shall be considered.

**5.5.2.2 Procedure:** Specimens may be axially loaded to consider effects of axial loads. The lateral load procedure consists of:

**5.5.2.2.1** Load specimens in both directions to find cracking and yielding load and deformation. For unreinforced masonry, only cracking load and deformation are required.

**5.5.2.2.2** The specimens are loaded in both directions until the strengthening system is damaged, its capacity is reached, or desired limit states are achieved.

### 5.6 Wall-to-Floor Joints:

**5.6.1 Configurations:** The specimens shall be configured to induce joint-related limit states or failure modes. Extremes of dimensional, reinforcing and compressive strength parameters shall be considered.

**5.6.2 Procedure:** For seismic or wind-loading applications, the lateral load procedure shall conform to Figure 1. For gravity load applications, the load may be monotonically applied. The vertical load shall be applied to floors. The limit states shall be determined based on material properties.

### 5.7 Slabs (Flexural Tests):

**5.7.1 Configuration:** Slab spans shall be configured to include flexural limit states or failure modes. Either simple or rigid supports are permitted. Extremes of dimensional, reinforcing and compressive strength shall be considered.

**5.7.2 Procedure:** For seismic or wind-load applications, the lateral load procedure shall conform to Figure 1. For gravity (nondynamic) loading application, the load may be monotonically applied. The limit states shall be determined based on material properties and an extreme concrete fiber compression strain of 0.003.

**5.8 Physical and Mechanical Properties of FRP Composite Materials:** Required physical and mechanical properties are shown in Table 1. These properties, including creep, CTE and impact, shall be considered in the design criteria and limitations.

### 5.9 Exterior Exposure:

**5.9.1 Procedure:** Structural FRP composite materials are tested according to ASTM G 153. Six specimens, measuring  $\frac{3}{4}$  inch by 10 inches (19.1 by 254 mm), are required. These specimens also may be cut from a panel that has been coated and painted to represent end-use conditions. Five specimens are exposed to cycles consisting of 102 minutes light and 18 minutes light and water spray in the weatherometer chamber. Minimum duration is 2,000 hours. The black-body temperature is 145°F (63°C). Both exposed and control specimens are then tested to ASTM D 3039, for tensile strength, tensile modulus and elongation. Five other specimens are controlled samples.

**5.9.2 Conditions of Acceptance:** Control and exposed specimens are visually examined using 5x magnification. Surface changes affecting performance, such as erosion, cracking, crazing, checking, and chalks, are subject to further investigation. The specimens shall retain at least 90 percent of tensile properties generated on control specimens.

### 5.10 Freezing and Thawing:

**5.10.1 Procedure:** Fifteen samples are conditioned in a 100 percent relative humidity chamber at 100°F (38°C) for three weeks. Each cycle is 4 hours, minimum, in a 0°F (-18°C) freezer followed by 12 hours, minimum, in the humidity chamber. At least twenty cycles are required.

Control specimens and cycled specimens are then tested according to Table 1 for tensile strength, tensile modulus, elongation, glass transition temperature, and interlaminar shear strength. Specimens are tested in the primary direction.

**5.10.2 Conditions of Acceptance:** Control specimens and cycled specimens are visually examined using 5x magnification. Surface changes affecting performance, such as erosion, cracking, crazing, checking and chalking, are unacceptable. The cycled specimens shall retain at least 90 percent of the tensile properties determined for conditioned specimens.

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

**5.11.1 Procedure:** Both wet and dry specimens are aged according to Table 2. Both exposed and control specimens are then tested to Table 1 for tensile strength, tensile modulus, elongation, glass transition temperature, and interlaminar shear strength. Specimens are tested in the primary direction. Five specimens per condition are required.

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

### 5.12 Alkali Soil Resistance:

**5.12.1 Procedure:** Tests are done on five specimens according to ASTM D 3083, Section 9.5, for 1,000 hours. Both conditioned and exposed specimens are then tested for tensile strength, tensile modulus, and elongation according to ASTM D 3039.

**5.12.2 Conditions of Acceptance:** Conditioned and exposed specimens are visually examined using 5x magnification. Surface changes, such as erosion, cracking, crazing, checking, and chalking, are unacceptable. The exposed specimens shall retain at least 90 percent of tensile properties generated on conditioned specimens.

**5.13 Fire-resistant Construction:** The effect of the FRP composite system on fire-resistance construction shall be evaluated according to Section 703 of the IBC or UBC.

**5.14 Interior Finish:** The classification of the fiber-reinforced polymer (FRP), composite system as an interior finish shall be determined according to Section 803 of the IBC or Section 802 of the UBC.

**5.15 Fuel Resistance:** Tested specimens are tested according to ASTM C 581. The specimens are exposed to diesel fuel reagent for 4 hours, minimum. Specimens are tested according to Table 1 for tensile strength, tensile modulus, elongation, glass transition temperature, and interlaminar shear strength.

**5.16 Adhesive Lap Strength:** This test applies to prefabricated systems. Specimens of the adhesive are tested according to ASTM D 3165 for exposures in Table 2, and Sections 5.10 and 5.15.

**5.17 Bond Strength:** The test applies to systems that bond to the substrate. Tests are conducted for tension according to ASTM D 4541 or ASTM C 297 where the composite material bonds two substrate elements together, and for shear using a method acceptable to ICC-ES staff. Specimens are exposed according to Table 2 and Section 5.10.

**5.18 Drinking Water Exposure:** The effect of the FRP composite system when directly exposed to drinking water shall be evaluated based in tests in accordance with NSF 61.

## 6.0 QUALITY CONTROL

**6.1 Manufacturing:** Quality assurance procedures during manufacture of the system components shall be described in a quality control manual complying with the ICC-ES Acceptance Criteria for Quality Documentation (AC10). The quality control program shall include periodic inspections by an inspection agency currently accredited by the International Accreditation Service, Inc. (IAS).

**6.2 Installation:** All installations shall be done by applicators approved by the proponent of the system. The

quality assurance program shall be documented and comply with AC178. Special inspection is required and shall comply with Section 1704 of the IBC or Section 1701 of the UBC and other sections of the applicable code. Duties of the special inspector shall be described and included in the evaluation report.

## 7.0 FINAL SUBMITTAL

**7.1** The final submittal will consist of a test report or test reports, and a design criteria report, as described in this section. The final submittal shall include the data described in Section 3 of this criteria. Contents of the final submittal are described in the following subsections:

**7.2 Test Report:** The independent laboratory shall report on the qualification testing performed according to the approved test plan. Besides the information requested in Section 4, the test report must include the following:

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

### 7.3 Design Criteria:

**7.3.1 Design Criteria Report:** The report shall include a complete analysis and interpretation of the qualification test results. Design stress and strain criteria for concrete and reinforced and unreinforced masonry systems shall be specified based on the analyses, but shall not be higher than specified in Section 7.3.2.

Design stresses and strains shall be based on a characteristic value approach verified by test data. The CTE and creep values determined in Table 1 shall be considered in the design procedure. The design criteria report shall provide guidance on protecting the composite materials in areas where they are prone to impact. The design shall consider secondary stresses resulting when dead loads are relieved during application and subsequently reapplied. Adoption of the minimum acceptable standards for design outlined in Section 7.3.2 does not eliminate the need for structural testing.

Situations not covered in Section 7.3.2 shall be subject to special considerations and testing, and design values should be compatible with the conservative approach adopted in Section 7.3.2, and discussed in reference [1].

### 7.3.2 Minimum Acceptable Design Criteria:

**7.3.2.1 Flexural Strength Enhancement:** Fiber-reinforced polymer (FRP) composite material bonded to surfaces of concrete or masonry may be used to enhance the design flexural strength of sections by acting as additional tension reinforcement. In such cases, section analysis shall be based on normal assumptions of a) plane sections remain plane after loading; b) the bond between the FRP and the substrate remains perfect; c) the maximum usable compressive strain in the concrete

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is 0.003; d) FRP has a linear elastic behavior to failure. The enhancement of axial force provided by a fiber element is

$$f_{ft} = E_f \epsilon_f \leq 0.75 f_{uj}(1)$$

where  $\epsilon_f$  is the strain in the concrete or masonry to which the fiber is bonded at the section strength in the direction of the member axis. Checks must be done to ensure that the strain in the member is at least as high as what is assumed in design. Fibers must not have a misalignment of more than 5 degrees.

Dependable flexural strengths shall be determined by multiplying the nominal flexural strength, including the effects of fiber according to Equation (1), by the appropriate flexural strength reduction factor according to the IBC or UBC.

**7.3.2.2 Bond Strength of Fiber to Concrete or Masonry:** Where the performance of the FRP composite material depends on bond, the bond strength of FRP composite material to concrete shall not be less than 200 psi (1378 kPa). The bond strength to masonry shall not be less than  $2.5\sqrt{f'_m}$ . In both cases, bond testing shall exhibit failure in the concrete or masonry substrate. Under ultimate flexural strength conditions, bond stress between FRP composite material and concrete or masonry shall not exceed

$$u_u = \frac{d(t_f f_f)}{dx} \leq 0.75 f_t \quad (2)$$

where  $x$  is the direction parallel to the fiber. Equation (2) should be evaluated at sections where rate of change in fiber net force  $t_f f_f$  is a maximum. This will normally correspond to locations of maximum shear force.

**7.3.2.3 Axial Load Capacity Enhancement:** FRP composite material may be bonded to external surfaces of concrete or masonry members to enhance axial load capacity.

Circular sections, and rectangular sections where the ratio of longer to shorter section side dimension is not greater than 1.5, may have axial compression capacity enhanced by the confining effect of FRP composite material placed with fibers running essentially perpendicular to the members' axis  $\theta \geq 75^\circ$  (transverse fiber).

**7.3.2.3.1 Circular Sections:** Compressive strength  $f'_{cc}$  of confined concrete of circular columns, diameter  $D$ , with fiber of effective thickness  $t_f$  at angle  $\theta \geq 75^\circ$  to the longitudinal axis of the member, shall be given by

$$f'_{cc} = f'_c \left[ 2.25 \sqrt{1 + 7.9 \frac{f_t}{f_c}} - 2 \frac{f_t}{f_c} - 1.25 \right] \quad (3)$$

where:

$$f_t = 0.26 \rho_{sj} f_{uj} \sin^2 \theta \quad (4)$$

and

$$\rho_{sj} = \frac{4t_f}{D} \quad (5)$$

**7.3.2.3.2 Rectangular Sections:** Compression strength  $f'_{cc}$  of confined concrete in rectangular columns of side lengths  $B$  and  $H$  where  $B \leq H \leq 1.5B$ , and with fiber of effective thickness  $t_f$  at angle  $\theta \leq 45^\circ$  to the longitudinal axis of the member, shall be given by

$$f'_{cc} = f'_c (1 + 1.5 \rho_{sj} \cos^2 \theta) \quad (6)$$

where:

$$\rho_{sj} = 2t_f \frac{(B+H)}{BH} \quad (7)$$

For rectangular sections confined with transverse FRP composite material, section corners must be rounded to a radius not less than  $3/4$  inch (20 mm) before placing FRP composite material. Axial compression capacity enhancement by FRP composite material to rectangular sections within aspect ratio  $H/B > 1.5$  shall be subject to special analysis confirmed by test results.

**7.3.2.4 Ductility Enhancement:** FRP 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 1.5. The enhancement is provided by increasing the effective ultimate compression strain of the section.

**7.3.2.4.1 Circular Sections:** Ultimate compression strain of circular sections of diameter  $D$ , confined with fiber of effective thickness  $t_f$  at angle  $\theta = 90^\circ$  to the longitudinal axis of the member, shall be given by

$$\epsilon_{cu} = 0.004 + \frac{2.5 \rho_{sj} f_{uj} \epsilon_{uj}}{f'_{cc}} \quad (8)$$

where  $f'_{cc}$  is given by Equation (3), and  $\rho_{sj}$  by Equation (5).

**7.3.2.4.2 Rectangular Sections:** Ultimate compression strains of rectangular sections of side lengths  $B$  and  $H$  where  $H \leq 1.5B$ , and with fiber of effective thickness  $t_f$  at an angle  $\theta$  to the longitudinal axis of the member, shall be given by

$$\epsilon_{cu} = 0.004 + \frac{1.25 \rho_{sj} f_{uj} \epsilon_{uj}}{f'_{cc}} \quad (9)$$

where  $f'_{cc}$  is given by Equation (6) and  $\rho_{sj}$  by Equation (7).

For rectangular sections confined with transverse FRP composite material, section corners must be rounded to a radius of not less than  $3/4$  inch (20 mm) before placing FRP composite material. Ductility enhancement according to Equation (9) should not be relied on for slender members where the aspect ratio  $M/VB \geq 3$ .

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**7.3.2.5 Lap-Splice Confinement:** Lap-splices in circular columns can be confined by jackets to prevent bond failure. The required volumetric ratio of FRP composite material, at an angle  $\theta$  to the longitudinal axis of the member given by Equation (5), shall not be less than

$$\rho_{sj} = \frac{1.4A_b f_s}{p l_s f_j} \quad (10)$$

where  $p$  is the perimeter of the crack surface forming before splice failure given by the lesser of Equations (11) and (12):

$$p = \frac{\pi D'}{2n} + 2(d_b + c) \quad (11)$$

$$p = 2\sqrt{2} (c + d_b) \quad (12)$$

In Equation (10), the circular section is reinforced with  $n$  bars each of diameter  $d_b$ , area  $A_b$ , uniformly distributed around the section on core diameter  $D'$ . Required stress to be transferred is  $f_s$ , and the splice length  $l_s$  must not be less than

$$l_s = \frac{0.025d_b f_y}{\sqrt{f'_c}} \quad (13)$$

$$\text{For SI: } s = \frac{0.3d_b f_y}{\sqrt{f'_c}}$$

The jacket stress  $f_j$  in Equation (1) shall not be taken larger than  $f_j = 0.0015 E_j \leq 0.75 f_{uj}$ .

**Note:** Rectangular sections cannot generally be effectively confined by rectangular jackets against splice failure, and so no provisions are included here.

**7.3.2.6 Shear Strength Enhancement:** Shear strength of circular and rectangular sections can be enhanced by FRP composite materials with fiber oriented essentially perpendicular to the members' axis.

**7.3.2.6.1 Circular Sections:** Nominal shear strength enhancement for circular sections of diameter  $D$ , with fiber thickness  $t_f$  at an angle  $\theta$  to the members' axis, shall be given by

$$V_{sj} = 2.25 t_f f_j D \sin^2 \theta \quad (14)$$

where

$$f_j = 0.004 E_j \leq 0.75 f_{uj} \quad (15)$$

**7.3.2.6.2 Rectangular Beam or Column Sections:** Nominal shear strength enhancement for rectangular sections or depth  $H$  parallel to the direction of applied shear force, with fiber thickness  $t_f$  at an angle  $\theta \geq 75^\circ$  to the members' axis, shall be given by

$$V_{sj} = 2.86 t_f f_j H \sin^2 \theta \quad (16)$$

where  $f_j$  is given by

$$f_j = 0.004 E_j \leq 0.75 f_{uj} \text{ (for completely wrapped on all four sides)}$$

$$f_j = 0.0015 E_j \leq 0.75 f_{uj} \text{ (for three-sided u-wraps)}$$

For rectangular sections with shear enhancement provided by transverse FRP composite material, section corners must be rounded to a radius not less than  $\frac{3}{4}$  inch (20 mm) before placement of the FRP composite material.

**7.3.2.6.3 Rectangular Wall Sections:** Nominal shear strength enhancement for rectangular wall sections of depth  $H$  parallel to the direction of applied shear force, with fiber thickness  $t_f$  on both sides of the wall at an angle  $\theta$  to the members' axis, shall be given by

$$V_{sj} = 2 t_f f_j H \sin^2 \theta \quad (17)$$

where  $f_j = 0.004 E_j \leq 0.75 f_{uj}$  (for completely wrapped on all four sides).

Where wall sections have fiber bonded to one side only at an angle  $\geq 75^\circ$  to the member axis, nominal shear strength enhancement shall be taken as

$$V_{sj} = 0.75 t_f f_j H \sin^2 \theta \quad (18)$$

where  $f_j = 0.0015 E_j \leq 0.75 f_{uj}$ .

Where wall sections have fiber bonded to one side at an angle  $\geq 75$  degrees to the member axis and with anchorage provided by bonding to the wall ends, the effective strain used to calculate  $f_j$  shall be determined through full-scale structural testing.

**7.3.2.6.4 Shear Strength Reduction Factor:** Dependable shear strength enhancement shall be found by multiplying the nominal shear strength given by Equations (14), (16), (17), or (18), as appropriate, by a shear strength reduction factor.

**Note:** These provisions do not apply to shear strength enhancement provided by fiber that does not extend the full section width bonding to perpendicular faces (section ends). These provisions do not apply to shear strength enhancement for flanged sections requiring placement of fiber around re-entrant corners. These cases must be subject to special study. The use of special anchors attaching the FRP composite material at the wall edges may be effective in transferring the design fiber stress between wall or beam and fiber.

**7.3.2.7 Enhancement Using Active Composite Systems:** Active FRP composite systems can be used to reduce the thickness of the FRP composite materials required and provide active confinement for the structural member. In such cases, analysis shall be based on assumptions verified by test results, including confining pressure, confining strain, creep and other durability considerations.

**7.4 Quality Control:** The quality control documents described Sections 6.1 and 6.2 shall be submitted.

**7.5 Nomenclature:**

- $d_b$  = reinforcement bar diameter, inches (mm).
- $B$  = width of compressive face of a rectangular column, inches (mm).
- $D$  = diameter of circular columns, inches (mm).
- $E_j$  = modulus of elasticity of FRP composite material, psi (MPa).
- $\Delta F$  = increase in axial force, lb (N).

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

$f'_m$  = specified compressive strength of masonry, psi (MPa).

$f'_t$  = tensile strength of concrete or masonry, psi (MPa).

$f_l$  = lateral confining stress, psi (MPa).

$f'_{cc}$  = confined compressive strength of confined columns, psi (MPa).

$f_{jf}$  = confining strength of FRP composite material, (MPa).

$f_{uj}$  = ultimate tensile strength of composite material, (MPa).

$f_j$  = hoop stress developed in jacket material, (MPa).

$H$  = side length of a rectangular column, inches (mm).

$l_s$  = reinforcement bar splice length, inches (mm).

$P$  = perimeter of cracked surface, inches (mm).

$P_{sj}$  = volumetric ratio of retrofit jacket.

$t_f$  = effective FRP composite material thickness.

$\mu$  = displacement ductility level, defined relative to yield or cracking displacement.

$M_u$  = bond strength between FRP composite material and concrete or masonry, psi (MPa).

$V_{sj}$  = shear strength enhancement provided by composite material, lb (N).

$\epsilon_c$  = concrete compression strain.

$\epsilon_{cu}$  = ultimate compression strain.

$\epsilon_f$  = strain composite material at designated strength.

$\epsilon_{uj}$  = ultimate strain of FRP composite material.

$\epsilon_{cc}$  = strain at peak stress for confined concrete.

$\theta$  = angle of fiber direction to member axis.

**References**

<sup>1</sup>Priestley, M.J. Nigel, Frieder Seible and Michele Calvi, *Seismic Design and Retrofit of Bridges* (Chapters 1 through 8). John Wiley and Sons, Inc., New York, September 1995, 672 pp.

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**TABLE 1—PHYSICAL PROPERTIES<sup>6</sup>**

PROPERTY	TEST METHOD	NO. OF SPECIMENS <sup>1</sup>
Tensile strength	ASTM D 3039	20 <sup>2</sup>
Elongation	ASTM D 3039	
Tensile modulus	ASTM D 3039	
Coefficient of thermal expansion (COE)	ASTM D 696 or ASTM E 831	5 <sup>2</sup>
Creep	ASTM D 2990 <sup>3</sup>	5 <sup>2</sup>
Void content	ASTM D 2584 <sup>4</sup> or D 3171 <sup>4</sup>	5
Glass transition (T <sub>g</sub> ) temperature	ASTM D 4065 or ASTM E 831 <sup>7</sup>	20 <sup>5</sup>
Composite interlaminar shear strength	ASTM D 2344	20

<sup>1</sup>Specimen sets shall exhibit a coefficient of variation (COV) of 6 percent or less. Outliers are subject to further investigation according to ASTM E 178. If the COV exceeds 6 percent, the numbered specimens shall be doubled.

<sup>2</sup>Values shall be determined in the primary and cross (90°) directions.

<sup>3</sup>Test duration is 3,000 hours, minimum.

<sup>4</sup>Maximum void content by volume is 6 percent.

<sup>5</sup>Minimum 140°F (60°C) T<sub>g</sub> is required for control and exposed specimens.

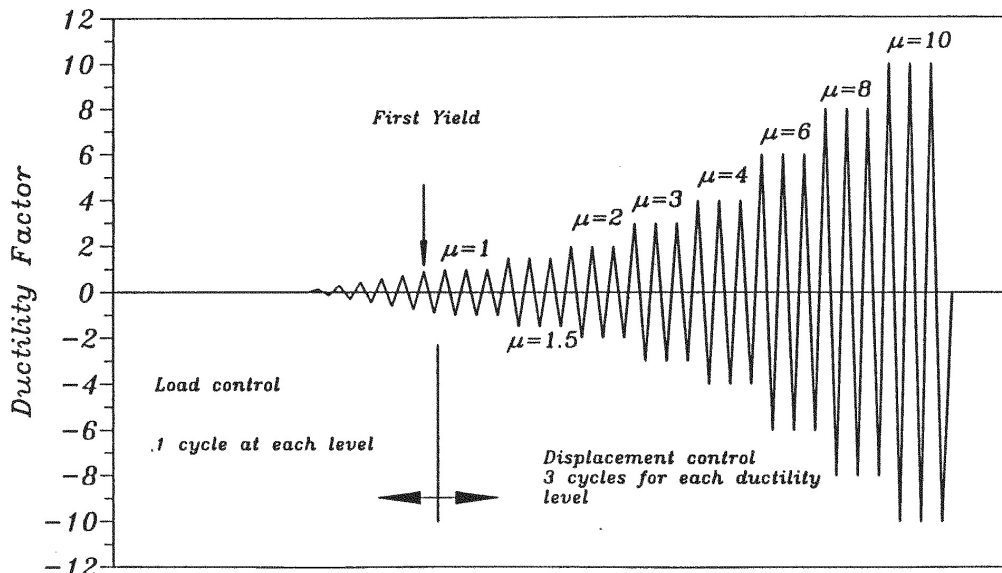
<sup>6</sup>For terminology, ASTM E 1142 is a reference.

<sup>7</sup>When using ASTM E 831, an Expansion versus Temperature curve as shown in Figure 1 of ASTM E 831 shall be developed; two tangents to the curve shall be plotted to coincide with the straightline portions of the curve above and below the inflection point. The point of intersection of these tangents shall be reported as T<sub>g</sub> for the material.

**TABLE 2—ENVIRONMENTAL DURABILITY TEST MATRIX**

ENVIRONMENTAL DURABILITY TEST	RELEVANT SPECIFICATIONS	TEST CONDITIONS	TEST DURATION	PERCENT RETENTION	
				Hours	
				1,000	3,000
Water resistance	ASTM D 2247 ASTM E 104	100 percent, 100 ± 2°F	1,000, 3,000 and 10,000 hours	90	85
Saltwater resistance	ASTM D 1141 ASTM C 581	Immersion at 73 ± 2°F	1,000, 3,000 and 10,000 hours		
Alkali resistance	ASTM C 581	Immersion in Ca (CO <sub>3</sub> ) at pH = 9.5 & 73 ± 3°F	1,000 and 3,000 hours		
Dry heat resistance	ASTM D 3045	140 ± 5°F	1,000 and 3,000 hours		

For SI: °C= (°F – 32)/1.8.



**FIGURE 1—TEST SEQUENCE OF IMPOSED DISPLACEMENT**