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

AC125

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PREFACE

Evaluation reports issued by ICBO Evaluation Service, Inc. (ICBO ES), are based upon performance features of the Uniform family of codes and the International family of codes. Section 104.2.8 of the *Uniform Building Code*™ (UBC), Section 104.11 of the *International Building Code*® (IBC) and Section R104.11 of the *International Residential Code*™ (IRC) are the primary charging sections upon which evaluation reports are issued. Section 104.2.8 of the UBC reads as follows:

> The provisions of this code are not intended to prevent the use of any material, alternate design or method of construction not specifically prescribed by this code, provided any alternate has been approved and its use authorized by the building official.
>
> The building official may approve any such alternate, provided the building official finds that the proposed design is satisfactory and complies with 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 suitability, strength, effectiveness, fire resistance, durability, safety and sanitation.
>
> The building official shall require that sufficient evidence or proof be submitted to substantiate any claims that may be made regarding its use. The details of any action granting approval of an alternate shall be recorded and entered in the files of the code enforcement agency.

Similar provisions are contained in Sections 104.11 and R104.11 of the IBC and IRC, respectively.

The attached acceptance criteria has been issued to provide all interested parties with guidelines on implementing performance features of the applicable code(s) referenced in the acceptance criteria. The criteria was developed and adopted following public hearings conducted by the 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 a previous edition, solid vertical lines (▌) in the outer margin within the criteria indicate a technical change or addition from the previous edition. Deletion indicators (➧) are provided in the outer margins where a paragraph or item has been deleted if the deletion resulted from a technical change. This criteria may be further revised as the need dictates.

ICBO ES may consider alternate criteria, provided the proponent submits valid data demonstrating that the alternate criteria are at least equivalent to the attached criteria and otherwise meet the applicable performance requirements of the codes. Notwithstanding that a material, type or method of construction, or equipment, meets the attached acceptance criteria, or that it can be demonstrated that valid alternate criteria are equivalent and otherwise meet the applicable performance requirements of the codes, if the material, product, system or equipment is such that either unusual care in its installation or use must be exercised for satisfactory performance, or malfunctioning is apt to cause unreasonable property damage or personal injury or sickness relative to the benefits to be achieved by the use thereof, ICBO ES retains the right to refuse to issue or renew an evaluation report.

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1.0 INTRODUCTION

1.1 Scope: These criteria establish minimum requirements for the issuance of ICBO Evaluation Service, Inc. (ICBO ES), evaluation reports on fiber-reinforced polymer (FRP) composite systems used to strengthen concrete and masonry structural elements. These reports consider these systems as alternates to those covered in the 1997 *Uniform Building Code™* (UBC) and the 2000 *International Building Code®* (IBC).

1.2 Referenced Documents:

1.2.1 1997 *Uniform Building Code™* (UBC), International Conference of Building Officials.

1.2.2 2000 *International Building Code®* (IBC), International Code Council.

1.2.3 ICBO ES Acceptance Criteria for Test Reports and Product Sampling (AC85).

1.2.4 ICBO ES Acceptance Criteria for Laboratory Accreditation (AC89).

1.2.5 ICBO ES Acceptance Criteria for Quality Control Manuals (AC10).

1.2.6 ASTM C 297-94, Test Method for Tensile Strength of Flat Sandwich Constructions in Flatwise Plane, American Society for Testing and Materials.

1.2.7 ASTM C 581-94, Practice for Determining the Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service, American Society for Testing and Materials.

1.2.8 ASTM D 1141-91, Practice for Preparation of Substitute Ocean Water, American Society for Testing and Materials.

1.2.9 ASTM D 2247-97, Practice for Testing Water Resistance of Coatings in 100% Relative Humidity, American Society for Testing and Materials.

1.2.10 ASTM D 2344-84 (1995), Test Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method, American Society for Testing and Materials.

1.2.11 ASTM D 2584-94, Test Method for Ignition Loss of Cured Reinforced Resins, American Society for Testing and Materials.

1.2.12 ASTM D 2990-95, Test Methods for Tensile, Compressive, and Flexural Creep and Creep Rupture of Plastics, American Society for Testing and Materials.

1.2.13 ASTM D 3029-94, Standard Test Methods for Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Tup (Falling Weight), American Society for Testing and Materials.

1.2.14 ASTM D 3039-95a, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, American Society for Testing and Materials.

1.2.15 ASTM D 3045-92, Standard Practice for Heat Aging of Plastics Without Load , American Society for Testing and Materials.

1.2.16 ASTM D 3083-89, Specification for Flexible Poly (Vinyl Chloride) Plastic Sheeting for Pond, Canal, and Reservoir Lining, American Society for Testing and Materials.

1.2.17 ASTM D 3165-95, Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-

Lap-Joint Laminated Assemblies, American Society for Testing and Materials.

1.2.18 ASTM D 3171-95, Standard Test Method for Constituent Content of Composite Materials, American Society for Testing and Materials.

1.2.19 ASTM D 4065-95, Standard Practice for Determining and Reporting Dynamic Mechanical Properties of Plastics, American Society for Testing and Materials.

1.2.20 ASTM E 104-85 (1996), Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions, American Society for Testing and Materials.

1.2.21 ASTM E 1142-97, Standard Terminology Relating to Thermophysical Properties, American Society for Testing and Materials.

1.2.22 ASTM G 23-96, Standard Practice for Operating Light-Exposure Apparatus (Carbon-Arc Type) With and Without Water for Exposure of Nonmetallic Materials, American Society for Testing and Materials.

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 ICBO ES evaluation report number (ICBO ES ER-xxxx).
2. Restrictions or limitations on use.

3.2 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 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 UBC or IBC.
2. Complete description of details.
3. Details on how the product or system does or does not comply with Chapter 19 of the UBC or IBC, including conformities and deviations. Details should include positive statements that the product or system does comply with Chapter 19 or 21 of the UBC or IBC 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 the ICBO ES Acceptance Criteria for Laboratory Accreditation (AC89).

4.2 Test reports and product sampling shall comply with the ICBO ES Acceptance Criteria for Test Reports and Product Sampling (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.

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 by 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 23-96. Six specimens, measuring $^{3}/_{4}$ 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. Both exposed and control specimens are then tested to ASTM D 3039-95a, 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 for three weeks. Each cycle is 4 hours, minimum, in a 0°F 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.

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 3083-89, 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 3039-95a.

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 fiber-reinforced polymer (FRP), composite system on fire-resistance construction shall be evaluated according to Section 703 of the UBC or IBC.

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

5.15 Fuel Resistance: Tested specimens are tested according to ASTM C 581-94. 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 3165-95 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 C 297-94 where the composite material bonds two substrate elements together, and for shear using a method acceptable to ICBO ES staff. Specimens are exposed according to Table 2 and Section 5.10.

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 ICBO ES Acceptance Criteria for Quality Control Manuals (AC10).

6.2 Installation: All installations shall be done by applicators approved by the proponent of the system. The quality assurance program shall be documented. Special inspection is required and shall comply with Section 1701 of the UBC or Section 1704 of the IBC and other sections of the applicable code. Duties of the special inspector shall be described and included in the evaluation report. The maximum debonded area permitted after installation of bonded systems is 2 square inches (1290.32 mm^2).

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, creep and impact values determined in Table 1, Section 5, shall be considered in the design procedure. 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 or compression reinforcement. In such cases, section analysis shall be based on normal assumptions of strain compatibility between concrete, reinforcement and FRP composite material. The enhancement of axial force provided by a fiber element of effective thickness t_f, oriented at angle θ to the direction of member axis, shall be

$$\Delta F = \frac{t_f \cos^2\theta f_{jf}}{\text{unit width}} \tag{1}$$

where $f_{jf} = E_f \varepsilon_f \cos^2\theta \le 0.75 f_{uj}$ and ε_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. Unless the compression zone is confined by transversely-oriented fiber outside the flexural fiber, an extreme compression strain of $\varepsilon_c = 0.003$ shall be assumed in determining flexural strength. If $\theta > 45°$, the fiber contribution to flexural strength shall be ignored unless equal fiber quantities are provided with an orientation of θ to the member axis.

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 UBC or IBC.

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 fiber-reinforced polymer (FRP) composite material to concrete or masonry shall not be less than the characteristic flexural tension capacity f_t' of the concrete or masonry. Under ultimate flexural strength conditions, bond stress between fiber-reinforced polymer (FRP) composite material and concrete or masonry shall not exceed

$$u_u = \frac{d(t_f\ f_j)}{dx} \le 0.75 f_t \tag{2}$$

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

7.3.2.3 Axial Load Capacity Enhancement: Fiber-reinforced polymer (FRP) composite material may be bonded to external surfaces of concrete or masonry members to enhance axial load capacity. Depending on the section shape, axial load capacity enhancement may be provided by longitudinal and/or transverse orientation of the fiber.

7.3.2.3.1 Longitudinal Fiber: All sections may have axial load capacity enhanced by fibers with a significant component of the angle parallel to member axes. In such cases, the principles stated in Section 7.3.2.1 shall apply with strength enhancement following Equation (1). Unless the section is effectively confined by transverse fiber with angle $\theta > 75°$ to the member axis, outside the longitudinal fiber, the enhancement of axial strength, given by Equation (1), shall apply at a fiber strain $\varepsilon_f = 0.002$. Where the section is effectively confined, a higher compression strain $\varepsilon_f = \varepsilon_{cu}$ may be used, where ε_{cu} is given by Equation (8) or (9).

7.3.2.3.2 Transverse Fiber: 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 fiber-reinforced polymer (FRP) composite material placed with fibers running essentially perpendicular to the members' axis $\theta \geq 75°$.

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

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

where

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

and

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

7.3.2.3.2.2 Rectangular Sections: Compression strength f'_{cc} of 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 $\theta \leq 45°$ to the longitudinal axis of the member, shall be given by

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

where

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

For rectangular sections confined with transverse fiber-reinforced polymer (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 fiber-reinforced polymer (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: Fiber-reinforced polymer (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 $\theta \approx 90°$ to the longitudinal axis of the member, shall be given by

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

where f'_{cc} is given by Equation (3), and ρ_{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 θ to the longitudinal axis of the member, shall be given by

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

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

For rectangular sections confined with transverse fiber-reinforced polymer (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 $M/VB \geq 3$.

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 fiber-reinforced polymer (FRP) composite material, at an angle θ to the longitudinal axis of the member given by Equation (5), shall be not less than

$$\rho_{sj} = \frac{1.4A_b\ f_s}{pl_s f_j} \qquad (10)$$

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

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

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

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

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

For **SI:** $s = \dfrac{0.3d_b f_y}{\sqrt{f'_{cu}}}$

The jacket stress f_j in Equation (10) shall not be taken larger than $f_j = 0.0015E_j \leq 0.75f_{uj}$.

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 fiber-reinforced polymer (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 θ to the members' axis, shall be given by

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

where

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

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 $\theta \geq 75°$ to the members' axis, shall be given by

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

where f_j is given by Equation (15).

For rectangular sections with shear enhancement provided by transverse fiber-reinforced polymer (FRP) composite material, section corners must be rounded to a radius not less than $^3/_4$ 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 θ to the members' axis, shall be given by

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

where f_j is given by Equation (15).

Where wall sections have fiber bonded to one side only at an angle ≥ 75° to the member axis and with anchorage provided by bonding to the wall ends, nominal shear strength enhancement shall be taken as

$$V_{sj} = 0.75 t_f\, f_j\, H \sin^2\theta \tag{18}$$

where f_j is given by Equation (15).

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 fiber-reinforced polymer (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 in 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).

ΔF = increase in axial force, lb (N).

f_t' = tensile strength of concrete or masonry, psi (MPa).

f_l = lateral confining stress, psi (MPa).

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

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

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

f_j = hoop stress developed in jacket material, psi (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.

μ = 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).

ε_c = concrete compression strain.

ε_{cu} = ultimate compression strain.

ε_f = strain composite material at designated strength.

ε_{uj} = ultimate strain of FRP composite material.

ε_{cc} = strain at peak stress for confined concrete.

θ = angle of fiber direction to member axis.

Reference

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.

TABLE 1—PHYSICAL PROPERTIES

PROPERTIES	TEST METHOD	NO. OF SPECIMENS[1]
Tensile strength	ASTM D 3039-95a	20[2]
Elongation	ASTM D 3039-95a	
Tensile modulus	ASTM D 3039-95a	
Coefficient of thermal expansion (CTE)	ASTM D 696-91 or E 1142-97	5[2]
Creep	ASTM D 2990-95[3]	5[2]
Void content	ASTM D 2584-94[5] or D 3171-95[5]	5
Glass transition (Tg) temperature	ASTM D 4065-95	20[6]
Impact	ASTM D 3029-94, Method 1[4]	5
Composite interlaminar shear strength	ASTM D 2344-84 (1995)	20

[1] 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.

[2] Values shall be determined in the primary and cross (90°) directions.

[3] Test duration is 3,000 hours, minimum.

[4] Impact head is 0.625 inch (15.9 mm). Specimens may be rectangular, measuring 4 inches by 6 inches (102 mm by 152 mm), and are placed on 3-inch-by-5-inch supports. 250 lb-in at 0.10 inch thick is the minimum requirement.

[5] Maximum void content by volume is 6 percent.

[6] Minimum 140°F (60°C) Tg is required for control and exposed specimens.

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 2247-97 ASTM E 104-85 (96)	100 percent, 100 ± 2° F	1,000, 3,000 and 10,000 hours	90	85
Saltwater resistance	ASTM D 1141-91 ASTM C 581-94	Immersion at 73 ± 2° F	1,000, 3,000 and 10,000 hours		
Alkali resistance	ASTM C 581-97	Immersion in Ca (CO$_3$) at pH=9.5 & 73 ± 3° F	1,000 and 3,000 hours		
Dry heat resistance	ASTM D 3045-92	140 ± 5° F	1,000 and 3,000 hours		

For **SI:** °C = (t°F – 32)/1.8.

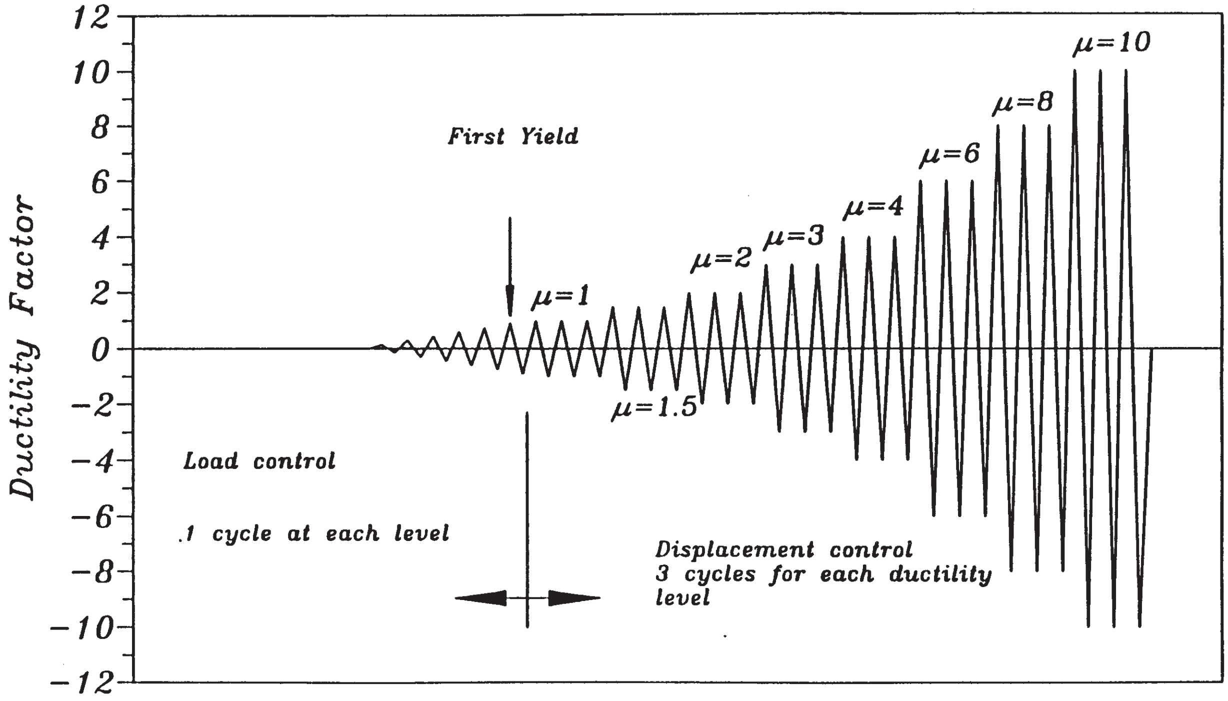

FIGURE 1—TEST SEQUENCE OF IMPOSED DISPLACEMENT