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

AC125

Approved February 2010

Effective March 1, 2010

Previously approved October 2009, June 2003, April 1997; editorially corrected June 2007

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*® 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.

ICC-ES may consider alternate criteria, provided the report applicant submits valid 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. Notwithstanding that a product, material, or type or method of construction meets the requirements of the criteria set forth in this document, or that it can be demonstrated that valid alternate criteria are equivalent to the criteria 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 an evaluation report, if the product, material, or type 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 unreasonable property damage or personal injury or sickness relative to the benefits to be achieved by the use of the product, material, or type or method of construction.

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

ACCEPTANCE CRITERIA FOR CONCRETE AND REINFORCED AND UNREINFORCED MASONRY STRENGTHENING USING EXTERNALLY BONDED FIBER-REINFORCED POLYMER (FRP) COMPOSITE SYSTEMS (AC125)

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 2009 and 2006 *International Building Code*® (IBC) and the 1997 *Uniform Building Code*™ (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.

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 Codes and Standards:

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

1.3.2 2006 *International Building Code*® (2006 IBC), International Code Council.

1.3.3 1997 *Uniform Building Code*™ (UBC), International Conference of Building Officials.

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

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

1.3.6 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.

1.3.7 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.

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

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

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

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

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

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

1.3.14 ASTM D 3039-00$^{\epsilon 2}$, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM International.

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

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

1.3.17 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.

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

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

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

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

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

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

1.3.24 ASTM G 153-04 Standard Practice for Operating Enclosed Carbon Arc Light Apparatus for Exposure of Nonmetallic Materials, ASTM 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. Active systems are outside the scope of this criteria.

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.

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 shall 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 shall 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 3. 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 3. 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 3. 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 3. 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 3. 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 3. 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 3. 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 2. 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 $^3/_4$ 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 5× 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 2 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 5× 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 3. Both exposed and control specimens are then tested to Table 2 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 5× 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 3.

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 5× 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 2 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 3, and Sections 5.10 and 5.15.

5.17 Bond Strength:

5.17.1 Procedure: 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 3~~2~~ and Section 5.10.

5.17.2 Conditions of Acceptance: The bond strength of FRP composite material to concrete shall not be less than 200 psi (1378 kPa). The bond strength of the FRP composite material to masonry shall not be less than 2.5 x $(f'_m)^{0.5}$. In both cases, bond testing shall exhibit failure in the concrete or masonry substrate.

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 values determined in Table 2 shall be considered in the design procedure. The creep rupture stress limits as shown 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 shall be compatible with the conservative approach adopted in Section 7.3.2, and discussed in reference [4].

7.3.2 Minimum Acceptable Design Criteria:

7.3.2.1 Flexural Strength Enhancement of Reinforced Concrete Members: Fiber-reinforced polymer (FRP) composite material bonded to surfaces of concrete 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 is 0.003; d) FRP 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 FRP-strengthened section include:

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

The effective strain in FRP reinforcement shall be limited to the strain level at which debonding may occur, ε_{fd}, as defined in Eq. (1a):

$$\varepsilon_{fd} = 0.083\sqrt{\frac{f'_c}{nE_f t_f}} \leq 0.9\varepsilon_{fu} \qquad (1a)$$

$$\varepsilon_{fd} = 0.41\sqrt{\frac{f_c'}{nE_f t_f}} \leq 0.9\varepsilon_{fu} \qquad \text{(SI Units)}$$

The nominal effective stress level in the FRP reinforcement shall be calculated in accordance with Equation (1b):

$$f_{fe} = 0.85 . E_f . \varepsilon_{fe} \text{ where } \varepsilon_{fe} \leq \varepsilon_{fd} \qquad (1b)$$

Checks must be done to ensure that the strain in the member is at least as high as what is assumed in design. Fibers shall 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 (1b), by the appropriate flexural strength reduction factor according to the IBC or UBC.

Design moment capacity for flexure shall be calculated in accordance with Equation (1c).

$$øM_n = ø(M_s+M_f) \qquad (1c)$$

7.3.2.1.1 Serviceability: The stress in the steel reinforcement under service load shall be limited to 80 percent of the yield strength.

$$f_{s,s} \leq 0.80 f_y \qquad (2)$$

7.3.2.1.2 Creep Rupture and Fatigue Stress Limits: The service stress levels in the FRP reinforcement under service load shall be limited to the values shown in Table 1.

7.3.2.2 Flexural Strength Enhancement of Masonry Elements: The flexural strength of a masonry element strengthened with FRP shall be based on the assumptions presented in Section 7.3.2.1. However, the effective strain in FRP reinforcement shall be limited to the strain level at which debonding may occur as defined in Equations (3a) and (3b):

$$\varepsilon_{fe} = 0.45\varepsilon_{fu} \qquad (3a)$$

$$f_{fe} = E_f \varepsilon_{fe} \qquad (3b)$$

The force per unit width provided by FRP shall be determined from Equation (4).

$$p_{fm} = nt_f f_{fe} \leq 1500\ lb/in \qquad (4)$$

$$p_{fm} = nt_f f_{fe} \leq 263\ kN/m \qquad \text{(SI units)}$$

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.

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 FRP composite material placed with fibers running essentially perpendicular to the members' axis.

The stress-strain for FRP-confined concrete is illustrated in Figure 1 and shall be determined using the following expressions:

$$f_c = \begin{cases} E_c\varepsilon_c - \dfrac{(E_c - E_2)^2}{4f'_c}(\varepsilon_c)^2 & 0 \leq \varepsilon_c \leq \varepsilon'_t \\ f'_c + E_2\varepsilon_c & \varepsilon'_t \leq \varepsilon_c \leq \varepsilon_{ccu} \end{cases} \qquad (5a)$$

$$\varepsilon'_t = \frac{2f'_c}{E_c - E_2} \qquad (5b)$$

$$E_2 = \frac{f'_{cc} - f'_c}{\varepsilon_{ccu}} \qquad (5c)$$

The maximum confined concrete compressive strength, f'_{cc}, and the maximum confinement pressure, f_l, shall be calculated using Equations (6) and (7), respectively with the inclusion of an additional reduction factor, $\psi_f = 0.95$.

$$f'_{cc} = f'_c + \psi_f 3.3 \kappa_a f_l \quad (6)$$

$$f_l = \begin{cases} \dfrac{2nt_f E_f \varepsilon_{fe}}{D} & \text{Circular Cross-section} \\ \dfrac{2nt_f E_f \varepsilon_{fe}}{\sqrt{b^2+h^2}} & \text{Non-circular Cross-section} \end{cases} \quad (7)$$

In Equation (7), the effective strain level in the FRP at failure, ε_{fe}, shall be given by:

$$\varepsilon_{fe} = 0.55\varepsilon_{fu} \quad (8)$$

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

The maximum compressive strain in the FRP-confined concrete, ε_{ccu}, shall not exceed 0.01 to prevent excessive cracking and the resulting loss of concrete integrity. The corresponding maximum value of f'_{cc} shall be calculated using the following stress-strain relationship:

$$\varepsilon_{ccu} = \varepsilon'_c \left(1.5 + 12\kappa_b \frac{f_l}{f'_c} \left(\frac{\varepsilon_{fe}}{\varepsilon'_c} \right)^{0.45} \right) \le 0.01 \quad (9)$$

In Equation (9), the efficiency factor, κ_b, shall be calculated using Equation (10b).

7.3.2.3.1 Circular Sections: For circular cross sections the shape factors κ_a and κ_b in Equations (6) and (9), respectively, shall be taken as 1.0.

7.3.2.3.2 Rectangular Sections: 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 > 2.0 shall be subject to special analysis confirmed by test results.

The shape factors κ_a in Equation (6) and κ_b in Equation (9) shall be calculated using Equation (10), and is shown in Figure 2.

$$\kappa_a = \frac{A_e}{A_c} \left(\frac{b}{h} \right)^2 \quad (10a)$$

$$\kappa_b = \frac{A_e}{A_c} \left(\frac{h}{b} \right)^{0.5} \quad (10b)$$

where,

$$\frac{A_e}{A_c} = \frac{1 - \left((b/h)(h-2r)^2 + (h/b)(b-2r)^2 \right) / (3A_g) - \rho_g}{1 - \rho_g} \quad (10c)$$

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 2.0. 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 θ = 90° to the longitudinal axis of the member, shall be given by

$$\varepsilon_{cu} = 0.004 + \frac{2.5\rho_{sj} f_{uj} \varepsilon_{uj}}{f'_{cc}} \quad (11)$$

where f'_{cc} is given by Equation (6), and ρ_{sj} is $(4t_f/D)$.

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

$$\varepsilon_{cu} = 0.004 + \frac{1.25\rho_{sj} f_{uj} \varepsilon_{uj}}{f'_{cc}} \quad (12)$$

where f'_{cc} is given by Equation (6) and ρ_{sj} is $2t_f[(B+H)/BH]$.

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 (12) shall not be relied on for slender members where the aspect ratio $M/VB \ge 3$.

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 FRP composite material, at an angle θ to the longitudinal axis of the member (ρ_{sj}) shall not be less than

$$\rho_{sj} \ge \frac{1.4 A_b f_s}{p l_s f_j} \quad (13)$$

where p is the perimeter of the crack surface forming before splice failure given by the lesser of Equations (14) and (15):

$$p = \frac{\pi D'}{2n} + 2(d_b + c) \quad (14)$$

$$p = 2\sqrt{2}\,(c + d_b) \quad (15)$$

In Equation (13), 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

$$l_s \ge \frac{0.025 d_b f_y}{\sqrt{f'_c}} \quad (16)$$

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

The jacket stress f_j in Equation (13) shall not be taken larger than $f_j = 0.0015E_j \leq 0.75\, f_{uj}$.

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 of Concrete Elements: Shear strength of circular and rectangular sections of concrete elements can be enhanced by FRP composite materials with fiber oriented essentially perpendicular to the members' axis.

Shear strengthening using external FRP 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. For external FRP reinforcement in the form of discrete strips, the center-to-center spacing between the strips shall not exceed the sum of d/4 plus the width of the strip.

The design shear strength of an FRP-strengthened concrete member can be determined using Eq. (17). An additional reduction factor shall be applied to the contribution of the FRP system, as follows:

0.85 for three-sided FRP U-wrap or two-sided strengthening schemes;

0.95 for fully wrapped sections.

$$\phi V_n = \phi\left(V_c + V_s + \psi_f V_f\right) \tag{17}$$

The shear contribution of the FRP shear reinforcement shall given by Equation (18)

$$V_f = \frac{A_{fv} f_{fe}(\sin\alpha + \cos\alpha) d_{fv}}{s_f} \tag{18}$$

where:

$A_{fv} = 2nt_f w_f$

$f_{fe} = \varepsilon_{fe} E_f$

The effective design strain ε_{fe} is the maximum strain that shall be achieved in the FRP system at the nominal strength and is governed by the failure mode of the FRP system and of the strengthened reinforced concrete member.

$\varepsilon_{fe} = 0.004 \leq 0.75\varepsilon_{fu}$ for completely wrapped members

$\varepsilon_{fe} = \kappa_v \varepsilon_{fu} \leq 0.004$ for 2-sides or 3-sides (U-wrapped) members

The bond-reduction coefficient shall be computed from Equations (19) through (22):

$$\kappa_v = \frac{k_1 k_2 L_e}{468\varepsilon_{fu}} \leq 0.75 \tag{19}$$

$$\kappa_v = \frac{k_1 k_2 L_e}{11{,}900\varepsilon_{fu}} \leq 0.75 \quad \text{(SI Units)}$$

$$L_e = \frac{2500}{(n_f t_f E_f)^{0.58}} \tag{20}$$

$$L_e = \frac{23{,}300}{(n_f t_f E_f)^{0.58}} \quad \text{(SI Units)}$$

$$k_1 = \left(\frac{f_c'}{4000}\right)^{2/3} \tag{21}$$

$$k_1 = \left(\frac{f_c'}{27}\right)^{2/3} \quad \text{(SI Units)}$$

$$k_2 = \begin{cases} 1 \ \text{for Completely wrapped} \\ \dfrac{d_{fv} - L_e}{d_{fv}} \ \text{for U - wrapped} \\ \dfrac{d_{fv} - 2L_e}{d_{fv}} \ \text{for two sides bonded} \end{cases} \tag{22}$$

The total shear strength provided by FRP and steel reinforcement shall be limited to the following:

$$V_s + V_f \leq 8\sqrt{f_c'} b_w d \tag{23}$$

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

For rectangular sections with shear enhancement provided by transverse 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.

7.3.2.6.1 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

$$V_{sj} = 2t_f f_j h \sin^2\theta \tag{24}$$

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 ≥ 75° to the member axis, nominal shear strength enhancement shall be taken as

$$V_{sj} = 0.75 t_j f_j h \sin^2\theta \tag{25}$$

where

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

Where wall sections have fiber bonded to one side at an angle ≥ 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.

7.3.2.6.2 Shear Strength Reduction Factor: Dependable shear strength enhancement shall be found by multiplying the nominal shear strength given by Equations (18), (24), or (25), 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.

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

7.5 Nomenclature:

A_c = cross-sectional area of concrete in compression member, in^2 (mm^2).

A_e = cross-sectional area of effectively confined concrete section, in^2 (mm^2).

A_g = gross area of concrete section, in^2 (mm^2).

A_{fv} = area of FRP shear reinforcement with spacing "s", in^2 (mm^2).

AFRP = Aramid fiber reinforced polymer

b = short side dimension of compression member of non-circular cross section, in. (mm).

b_w = web width or diameter of circular section, in. (mm).

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

CFRP = Carbon fiber reinforced polymer.

D = diameter of circular columns, inches (mm).

d_b = reinforcement bar diameter, inches (mm).

d_{fv} = effective depth of FRP shear reinforcement, in (mm).

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

~~E_j~~E_f = modulus of elasticity of FRP composite material, psi (MPa).

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

ΔF = increase in axial force, lb (N).

f_c = compressive stress in concrete, psi (MPa)

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

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

f_{fe} = effective stress in the FRP; stress level attained at section failure, psi (MPa)

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

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

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

f_{fe} = effective stress in the FRP; stress level attained at section failure, 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).

GFRP = Glass fiber reinforced polymer.

h = long side length of a rectangular column, inches (mm).

k_1 = modification factor applied to κ_v to account for concrete strength.

k_2 = modification factor applied to κ_v to account for wrapping scheme.

L_e = active bond length of FRP laminate, in.

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

p = perimeter of cracked surface, inches (mm).

p_{fm} = force per unit width that the FRP system transfers to the masonry substrate,lb/in (N/m)

p_{sj} = volumetric ratio of retrofit jacket.

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

n = number of plies of FRP reinforcement.

r = radius of edges of a non-circular cross section confined with FRP, in. (mm).

s_f = center-to-center spacing of FRP shear reinforcement, in (mm).

t_f = effective FRP composite material thickness.

V_f = shear strength enhancement provided by composite material, lb (N).

V_c = nominal shear strength provided by concrete with steel flexural reinforcement, lb (N).

V_s = nominal shear strength provided by steel stirrups, lb (N).

w_f = width of FRP reinforcing plies, in. (mm).

α = angle of fiber inclination to member axis, degrees.

ε_c = concrete compression strain.

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

ε_{cu} = ultimate compression strain of unconfined concrete.

ε_{ccu} = ultimate compression strain of confined concrete.

ε_f = strain composite material at designated strength.

ε_{fe} = effective strain level in FRP reinforcement attained at failure, in/in (mm/mm).

ε_{fd} = debonding strain of externally bonded FRP reinforcement.

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

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

ϕ = strength reduction factor.

κ_a = efficiency factor for FRP reinforcement in determination of f'_{cc} (based on geometry of cross section).

κ_b = efficiency factor for FRP reinforcement in determination of ε_{ccu} (based on geometry of cross section).

κ_v = bond-dependent coefficient for shear.

κ_ε = efficiency factor equal to 0.55 for FRP strain to account for the difference between observed rupture strain in confinement and rupture strain determined from tensile tests.

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

ρ_g = ratio of area of longitudinal steel reinforcement to cross-sectional area of a compression member.

ψ_f = FRP strength reduction factor.

= *0.85 for flexure (calibrated based on design material properties).*

= *0.85 for shear (based on reliability analysis) for three-sided FRP U-wrap or two-sided strengthening schemes.*

= *0.95 for shear fully wrapped sections.*

Referenced Documents

1) ACI Committee 440.2R-08, 2008, "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures," American Concrete Institute, Farmington Hills, MI.

2) Concrete Society, "Design Guidance for Strengthening Concrete Structures Using Fibre Composite Materials," Technical Report No. 55 (TR55), second edition, Surrey, 2004.

3) Pessiki, S.; Harries, K. A.; Kestner, J.; Sause, R.; and Ricles, J. M., "*The Axial Behavior of Concrete Confined with Fiber Reinforced Composite Jackets*," Journal of Composites in Construction, ASCE, V. 5, No. 4, 2001, pp. 237-245.

4) 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.

5) Lam, L., and Teng, J., "Design-Oriented Stress-Strain Model for FRP-Confined Concrete," Construction and Building Materials, V. 17, 2003a, pp. 471-489.

6) Lam, L., and Teng, J., "Design-Oriented Stress-Strain Model for FRP-Confined Concrete in Rectangular Columns," Journal of Reinforced Plastics and Composites, V. 22, No. 13, 2003b, pp. 1149-1186.

7) NSF 61-2003e, Drinking Water Components—Health Effects, NSF International. ■

TABLE 1—CREEP RUPTURE STRESS LIMITS IN FRP REINFORCEMENT

PARAMETER	Fiber Type		
Stress Type	GFRP	AFRP	CFRP
Creep Rupture	$0.20f_{uj}$	$0.30f_{uj}$	$0.55f_{uj}$

TABLE 2—PHYSICAL PROPERTIES[6]

PROPERTY	TEST METHOD	NO. OF SPECIMENS[1]
Tensile strength	ASTM D 3039	20[2]
Elongation	ASTM D 3039	
Tensile modulus	ASTM D 3039	
Coefficient of thermal expansion (~~COE~~ CTE)	ASTM D 696 or ASTM E 831	5[2]
Creep[8]	ASTM D 2990[3]	5[2]
Void content	ASTM D 2584[4] or D 3171[4]	5
Glass transition (Tg) temperature	ASTM D 4065 or ASTM E 831[7]	20[5]
Composite interlaminar shear strength	ASTM D 2344	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 number of 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]Maximum void content by volume is 6 percent.
[5]Minimum 140°F (60°C) Tg is required for control and exposed specimens.
[6]For terminology, ASTM E 1142 is a reference.
[7]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 Tg for the material.
[8]Creep stresses for design shall be the lesser of the analysis of test or the maximum values in Table 1.

TABLE 3—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_3) 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= (t°F – 32)/1.8.

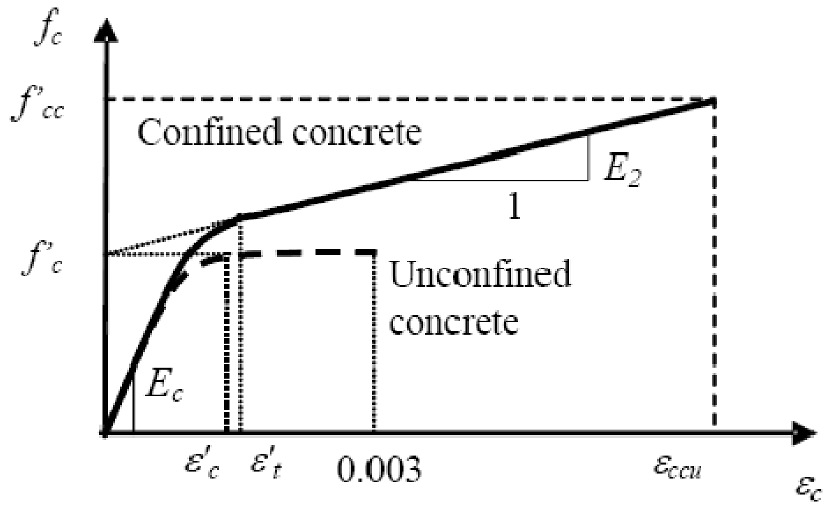

FIGURE 1—STRESS-STRAIN DIAGRAM FOR FRP-CONFINED CONCRETE

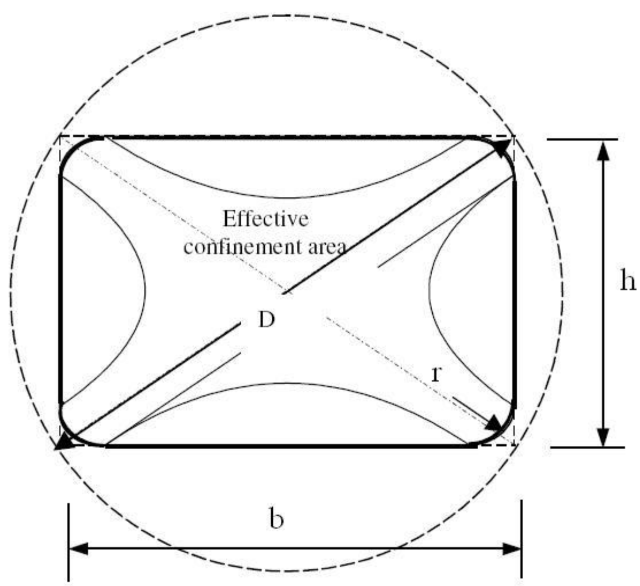

FIGURE 2—EQUIVALENT CIRCULAR CROSSSECTION

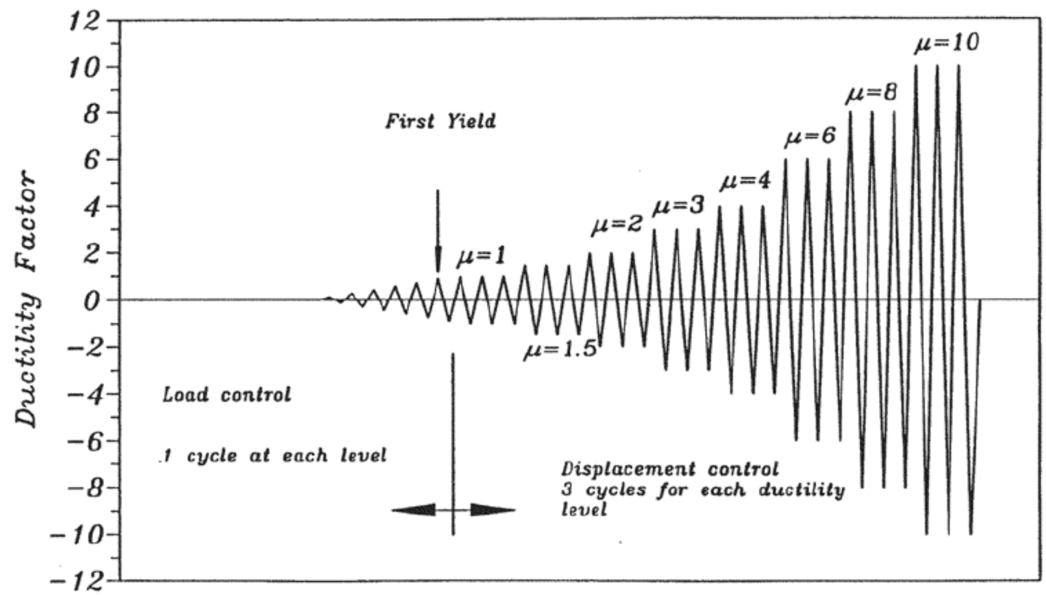

FIGURE 3—TEST SEQUENCE OF IMPOSED DISPLACEMENT