SECTION II:

RECOMMENDED CONSTRUCTION SPECIFICATIONS
1 GENERAL

These specifications are intended for use in the construction of bonded repair and retrofit of concrete structures using fiber reinforced polymer (FRP) composites. These specifications do not include design aspects of FRP systems or the extent or limitations of the repair and retrofit of an existing concrete structure.

1.1 Scope

These specifications cover construction of FRP systems used as externally bonded or near surface mounted reinforcement to enhance axial, shear, or flexural strength or ductility of a concrete member, such as column, beam, slab, or wall.

1.2 Definitions

The following terms used in these specifications are primarily taken from ACI 440.2R-02 with some changes:

Batch—A quantity of material formed during the same field installation in one continuous process and having identical characteristics throughout.

Bidirectional Laminate—Reinforced polymer laminate with fibers oriented in two different directions in its plane.

Binder—Resin constituent that holds together the other constituents of an FRP composite.

Bond-Critical Applications—Applications of FRP systems for strengthening structures that rely on bond to the concrete substrate. Examples are flexural and shear strengthening of beams and slabs.

Catalyst—A substance that initiates a chemical reaction and enables it to proceed under milder conditions than otherwise required and that does not, itself, alter or enter into the reaction. See hardener.

C1 GENERAL

FRP systems may be used to increase live load capacity of a structure, repair members that are damaged by impact or corrosion, reduce stresses in the internal steel reinforcement, or increase ductility in seismic retrofit. For design issues, consult with relevant guidelines such as ACI 440.2R-02.

C1.1 Scope

FRP systems may include externally bonded sheets, strips, plates, and shells and near surface mounted FRP bars and strips that are bonded inside a groove cut into the surface of concrete.

C1.2 Definitions

The definitions of the terms given herein are for consistent application of these specifications and may not always correspond to the ordinary usage of the term. For a glossary of the most commonly used terms related to concrete construction and FRP systems, consult with ACI 116R-00, ACI 440R-96, and ACI 440.2R-02.
Composite—A combination of two or more materials differing in form or composition on a macroscale. The constituents retain their identities; they do not dissolve or merge completely into one another, although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another. See composite FRP.

Composite FRP—A polymer matrix, either thermosetting or thermoplastic, reinforced with a fiber or other material with a sufficient aspect ratio (length to thickness) to provide a discernible reinforcing function in one or more directions. See composite.

Contact-Critical Applications—Applications of FRP systems that rely on intimate contact between concrete substrate and the FRP system to function as intended. An example is the confinement of columns for seismic retrofit. In these specifications, contact-critical applications are treated in the same way as bond-critical applications. See bond-critical applications.

Creep Rupture—Failure of an FRP system resulting from a gradual, time-dependent reduction of capacity due to sustained loading.

Cure—The process of causing irreversible changes in the properties of a thermosetting resin by chemical reaction. Cure is typically accomplished by addition of curing agents or initiators, with or without heat and pressure. Full cure is the point at which a resin reaches its specified properties. Resin is undercured if its specified properties have not been reached.

Cure Time—The time necessary to cure a thermosetting resin system, thermoset-based composite, or prepreg at a given temperature.

Curing Agent—A catalytic or reactive agent that, when added to resin, causes polymerization. Also called hardener.
SPECIFICATIONS

**Debonding**—A separation at the interface between substrate and the reinforcing layer.

**Delamination**—Separation of the layers of the FRP laminate from each other.

**Development Length**—The bonded distance required for transfer of stresses from concrete to the FRP to develop tensile capacity of FRP.

**Durability**—The ability of a material to resist cracking, oxidation, chemical degradation, delamination, wear, or the effects of foreign object damage for a specified period of time, under the appropriate load conditions and specified environmental conditions.

**Epoxy**—A polymerizable thermosetting polymer containing one or more epoxide groups, cured by reaction with phenols, anhydrides, polyfunctional amines, carboxylic acids, or mercaptans. An important matrix resin in FRP; also used as structural adhesive.

**Fabric**—Arrangement of fibers held together in two or three dimensions. It may be woven, non-woven, knitted or stitched. Fabric architecture is the specific description of the fibers, their directions and construction.

**Fiber**—A general term used to refer to filamentary materials. The smallest unit of a fibrous material. Often, fiber is used synonymously with filament.

**Fiber Content**—The amount of fiber present in a composite, usually expressed as a volume fraction or a mass fraction of the composite.

**Fiber Fly**—Short filaments that break off dry fiber tows or yarns during handling and become airborne, classified as nuisance dust.
Fiber Reinforced Polymer (FRP) System—Composite material consisting of a polymer matrix reinforced with cloth, mat, strands, or any other fiber form. See composite.

Filament—See fiber.

Filler—A relatively inert substance added to a resin to alter its properties or to lower cost or density. Also used to term particulate additives. Also called extenders.

Fire Retardant—Chemicals used to reduce the tendency of resin to burn. They can be added to the resin or coated on the surface of the FRP.

Flow—The movement of uncured resin under pressure or gravity loads.

Glass Transition Temperature ($T_g$)—The approximate midpoint of the temperature range over which a transition in material response from elastic to viscoelastic takes place [ASM 2001].

Hardener—Substance added to thermosetting resin to cause polymerization. Usually applies to epoxy resins.

Impregnation—The process of saturating the interstices of a reinforcement or substrate with a resin.

Inhibitor—A substance that retards a chemical reaction, such as ultraviolet degradation. Also used to prolong shelf life of certain resins.

Initiator—Chemicals, most commonly peroxides, used to initiate the curing process for unsaturated polyester and vinyl ester resins. See catalyst.

Laminate—one or more layers or plies of fiber, boded together in a cured resin matrix.

Lay-Up—The process of placing the FRP reinforcing material in position for installation.
SPECIFICATIONS

Lot—A quantity of material manufactured during the same plant production in one continuous process and having identical characteristics throughout. In these specifications, batch is used interchangeably. See batch.

Mat—A fibrous material for reinforced polymer consisting of randomly oriented chopped filaments, short fibers (with or without a carrier fabric), or long random filaments loosely held together with a binder.

Matrix—The essentially homogeneous resin or polymer material in which the fiber system of a composite is embedded.

Micro-Cracking—Cracks formed in composites when stresses locally exceed the strength of the matrix.

MSDS—Material Safety Data Sheet.

Near Surface Mounted (NSM)—Alternative repair system, where an FRP bar or strip is inserted and anchored into a precut groove.

Pin Holes—A small cavity, typically less than 1.5 mm (0.06 in.) in diameter, that penetrates the surface of a cured composite part.

Pitch—Petroleum or coal tar precursor base used to make carbon fiber.

Ply—A single layer of fabric or mat.

Polyester—A thermosetting polymer synthesized by the condensation reaction of certain acids with alcohols and subsequently cured by additional polymerization initiated by free radical generation. Polyesters are used as binders for resin mortars and concretes, fiber laminates, and adhesives. Commonly referred to as “unsaturated polyester.”
Polymer—A compound formed by the reaction of simple molecules that permit their combination to proceed to high molecular weights under suitable conditions.

Polyurethane—A thermosetting resin prepared by the reaction of disocyanates with polyols, polyamides, alkyd polymers, and polyether polymers.

Postcure—Additional elevated-temperature cure to increase the level of polymer cross linking; final properties of the laminate or polymer are enhanced.

Pot Life—Time that a catalyzed resin retains a viscosity low enough to be used in processing. Also called working life.

Prepreg—A fiber or fiber sheet material containing resin whose reaction has progressed to the stage where consistency is tacky. Multiple plies of prepreg are typically cured with applied heat and pressure. Also preimpregnated fiber or sheet.

Pultrusion—A continuous process that combines pulling and extrusion for manufacturing composites that typically have a constant cross-sectional shape. The process consists of pulling a fiber material through a resin bath and then through a heated shaping die, where the resin is cured.

Resin—A component of a polymeric system that requires a catalyst or hardener to polymerize or cure for use in composites. Resin often refers to the mixed polymer component or matrix of the FRP.

Resin Content—The amount of resin in a laminate expressed as a percentage of either total mass or total volume.

Roving—A number of yarns, strands, tows, or ends of fibers collected into a parallel bundle with little or no twist.
SPECIFICATIONS

**Shelf Life**—The length of time a material, substance, product, or reagent can be stored under specified environmental conditions and continue to meet all applicable specifications or remain suitable for its intended function. Also called storage life.

**Structural Adhesive**—A resinous bonding agent used for transferring required loads between adherents.

**Substrate**—The original concrete and any cementitious repair materials used to repair or replace the original concrete. It can consist entirely of original concrete, entirely of repair materials, or of a combination of the two. The FRP is installed on the surface of the substrate.

**Thermoplastic**—A non-cross-linked polymer capable of being repeatedly softened by an increase of temperature and hardened by a decrease in temperature. Examples are nylon, polypropylene, and polystyrene.

**Thermoset**—A cross-linked polymer that cannot be softened and reformed by an increase in temperature. Cross linking is an irreversible process; thermosets cannot be returned to a molten state. Examples are epoxy, phenolic, and vinyl ester.

**Tow**—An untwisted bundle of continuous filaments.

**Unidirectional Laminate**—A reinforced polymer laminate in which substantially all of the fibers are oriented in the same direction.

**Vinyl Ester**—A polymerizable thermosetting resin containing vinyl and ester components, cured by additional polymerization initiated by free-radical generation. Vinyl esters are used as binders for fiber laminates and adhesives.
**Viscosity**—The property of resistance to flow exhibited within the body of a material, expressed in centipoises. A higher viscosity has higher resistance to flow.

**Volatile**—Materials such as water and solvents in a resin formulation that are capable of being driven off as vapor.

**Wet Lay-Up**—A method of making a laminate system by applying the resin system as a liquid, when the fabric or mat is put in place.

**Wet-Out**—The process of coating or impregnating roving, yarn, or fabric in which all voids between the strands and filaments are filled with resin. It is also the condition at which this state is achieved.

**Wetting Agent**—A substance capable of lowering surface tension of liquids, facilitating the wetting of solid surfaces and permitting the penetration of liquids into the capillaries.

**Witness Panel**—A small FRP panel, manufactured on site under conditions similar to the actual construction. The panel may be later tested to determine mechanical and physical properties to confirm the expected properties for the full FRP structure.

### 1.3 Recommended References

The following standards or documents are referred to in these specifications:

**ACI—American Concrete Institute**
- 116R-00: Cement and Concrete Terminology.
- 224.1R-93: Causes, Evaluation, and Repair of Cracks in Concrete Structures.
- 224R-01: Control of Cracking in Concrete Structures.
SPECIFICATIONS

- 503R-93: Use of Epoxy Compounds with Concrete.
- 503.4-92: Standard Specification for Repairing Concrete with Epoxy Mortars.
- 503.5R-92: Guide for the Use of Polymer Adhesives in Concrete.
- 503.6R-97: Guide for the Application of Epoxy and Latex Adhesives for Bonding Freshly Mixed and Hardened Concrete.
- 546R-96: Concrete Repair Guide.

ASTM—American Society for Testing and Materials


ICBO—International Conference of Building Officials

ICRI—*International Concrete Repair Institute*

- No. 03730: Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion.
- No. 03732: Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays.
- No. 03733: Guide for Selecting and Specifying Materials for Repairs of Concrete Surfaces.

### 1.4 Tolerances

Tolerances recommended by the manufacturer shall be followed, unless more stringent requirements are specified in these specifications or in the contract documents. In case of any conflict or appearance of any conflict, the engineer shall provide clarification before proceeding.

### 1.5 Site Considerations

The contractor shall provide necessary pathways; scaffoldings; and other means of access to the general project site and to the specific repair area for the personnel, equipment, and materials. All obstructions such as pipes, conduits, and wiring shall be removed at the expense of the contractor, upon approval of the engineer and after making records for subsequent reinstallation by the contractor at the completion of the project. Plants, fences, and other obstructions that prevent access for repair shall be removed and, upon approval of the engineer, reinstalled or disposed of according to Section 3.4, at the expense of the contractor.

### 1.6 Fire Considerations

Fire is a life safety issue with the design of FRP systems. Most FRP systems are assumed to be lost completely in a fire due to their low temperature resistance.

### 2 SUBMITTALS

The contractor shall submit the following documents for the engineer’s approval before starting the work.

---

**C1.4 Tolerances**

Adherence to proper tolerances is necessary to produce acceptable work. It is important to avoid accumulating tolerances. The owner may accept the manufacturer tolerances if appropriate test data are shown that warrant the change based on the unique characteristics of a particular system.

**C1.5 Site Considerations**

FRP systems can generally be installed in most locations with very limited access and minimal equipment. In most applications, the impact of the FRP system on the existing utilities is minimal.

**C1.6 Fire Considerations**

Fire resistance of FRP systems may be improved by adding fire retardants to the resin or by coating on the surface of the FRP. Other methods of fire protection may also be used.
2.1 Working Drawings

Working (shop) drawings shall include the type of FRP system, repair locations, relevant dimensions of the system, and the work plan including the necessary preparations of the existing structure. The drawings must be accompanied by the design calculations, the MSDS, and the manufacturer’s system data sheet identifying mechanical, physical, and chemical properties of all components of the FRP system; application guide, including the installation and maintenance procedures; and time schedule for various steps in the repair process. The installation procedure must clearly identify the environmental and substrate conditions that may affect the application and curing of the FRP system.

2.2 Quality Control/Quality Assurance Plan

The contractor shall be responsible for the quality control of all materials and processes in the project. The quality control and quality assurance (QC/QA) plan must be approved by the owner or its representative. It shall include specific procedures for personnel safety, tracking and inspection of all FRP components prior to installation, inspection of all prepared surfaces prior to FRP application, inspection of the work in progress to ensure conformity with specifications, QA samples, inspection of all completed work including necessary tests for approval, repair of any defective work, and clean-up. Any part of the work that fails to comply with the requirements of the contract documents shall be rejected by the engineer and shall be remedied or removed and replaced by the contractor at its own expense to be in full compliance with the contract documents.

2.3 Qualifications

The manufacturer/supplier must be pre-qualified by the owner or its representative for each of its FRP systems after providing the following necessary information:

C2.1 Working Drawings

The necessary information for each FRP system may be different. Shop drawings for wet lay-ups may include, for example, fiber orientation, nominal thickness, aerial weight of dry fabric, number of layers, fiber volume or weight fraction, locations and lengths of lap splices, end details, and anchoring. Shop drawings for near surface mounted FRP may include, for example, locations and sizes of grooves and bars or strips. Shop drawings may also include necessary corner radii and surface conditions of the existing structure. The system data sheets may also include, for example, mix ratio, pot life, temperature-cure time data, gel time at proposed cure temperature, and acceptable humidity and temperature ranges for mixing and applying the resin.

C2.2 Quality Control/Quality Assurance Plan

The QC/QA program should be comprehensive and cover all aspects of the FRP system. QA is achieved through a set of inspections and applicable tests to document the acceptability of the installation. Details of the plan in terms of inspection, testing, and record keeping may be developed to match the size and complexity of the project. Additional information regarding the necessary elements of the QC/QA plan is included in the process control manual that accompanies this document. The manual ensures that the specifications are followed and provides guidance and specific checklists for QA by the owner or its representative.

C2.3 Qualifications

Qualification of the manufacturer/supplier for each of its FRP systems ensures acceptability of the system, as well as competence of the manufacturer/supplier to provide it. The owner or its rep-
SPECIFICATIONS

1) System data sheets and MSDSs for all components of the FRP system;
2) A minimum of 5 years of documented experience or 25 documented similar field applications with acceptable reference letters from respective owners;
3) A minimum of 50 test data sets (total) from an independent agency approved by the owner on mechanical properties, aging and environmental durability of the system; and
4) A comprehensive hands-on training program for each FRP system to qualify contractors/applicators.

The contractor/applicator must be pre-qualified by the owner or its representative for each FRP system after providing the following necessary information:
1) A minimum of 3 years of documented experience or 15 documented similar field applications with acceptable reference letters from respective owners and
2) A certificate of completed training from the manufacturer/supplier for at least one field representative who will be present on site throughout the project.

COMMENTARY

representative may also require the manufacturer/supplier to provide a specified number of samples of the components and the complete FRP system for in-house or independent testing prior to qualification. The owner may accept the total experience of the key personnel on similar field applications. For specific items on system data sheets, refer to Section C2.1. Test data sets may follow appropriate protocols such as those developed by the Highway Innovative Technology Evaluation Center (HITEC) [Reynaud et al. 1999, CERF 2001]. The training program by the manufacturer/supplier should provide hands-on experience with surface preparation and installation of the same FRP system for which the certificate is issued.

Qualification of the contractor/applicator for each FRP system ensures competence of the contractor/applicator for surface preparation and application of a particular FRP system through evidence of appropriate training and related past experience. The owner may accept the total experience of the key personnel on similar field applications. The field representative may be employed by either the contractor/applicator or the manufacturer/supplier.

C3 STORAGE, HANDLING AND DISPOSAL

C3.1 Storage

C3.1.1 Storage Requirements

These requirements are intended to help preserve properties of the FRP system and maintain the safety of the work place. The components may include sheets, plates, bars, strips, resins, solvents, adhesives, saturants, putty, and protective coatings. The system identification number may be the batch number from the factory. Typically, temperature in the storage area should be within 10–24°C (50–75°F), unless otherwise noted on the system data sheet. Typically, components should be delivered and stored in the original factory-sealed, unopened packaging or in containers with proper labels identifying the manufacturer, brand name, system identification number, and date. Catalysts and initiators should be stored separately. All components must be protected from dust, moisture, chemicals, direct sunlight, physical damage, fire, and temperatures outside the range specified in the system data sheets. Any component that has been
SPECIFICATIONS

stored in a condition different from that stated above must be disposed of, as specified in Section 3.4.

3.1.2 Shelf Life

All components of the FRP system, especially resins and adhesives, that have been stored longer than the shelf life specified on the system data sheet shall not be used and must be disposed of, as specified in Section 3.4.

3.2 Handling

All components of the FRP system, especially fiber sheets, must be handled with care according to the manufacturer recommendations to protect them from damage and to avoid misalignment or breakage of the fibers by pulling, separating, or wrinkling them or by folding the sheets. After cutting, sheets shall be either stacked dry with separators or rolled gently at a radius no tighter than 305 mm (12 in.) or as recommended by the manufacturer.

3.2.1 Safety Hazards

All components of the FRP system, especially resins and adhesives, must be handled with care to avoid safety hazards, including but not limited to skin irritation and sensitization and breathing vapors and dusts. Mixing resins shall be monitored to avoid fuming and inflammable vapors, fire hazards, or violent boiling. The contractor is responsible for ensuring that all components of the FRP system at all stages of work conform to the local, state, and federal environmental and worker’s safety laws and regulations.

3.2.2 Material Safety Data Sheets

The MSDSs for all components of the FRP system shall be accessible to all at the project site. Specific handling hazards and disposal instructions shall be specified in the MSDSs.

3.2.3 Personnel and Workplace Protection

The contractor is responsible for providing the proper means of protection for safety of the personnel and the workplace. The contractor shall

COMMENTARY

stored in a dry environment, unless an acceptable moisture level is specified on the system data sheet.

C3.1.2 Shelf Life

Properties and reactivity of resins and adhesives may degrade with time, temperature, or humidity.

C3.2 Handling

Fiber sheets with higher modulus fibers are more susceptible to misalignment damages and therefore must be handled with greater care. Dusts or residue can enter fiber sheets if not protected. Rolling precut short lengths of fiber sheets may cause damage through fiber movement and fabric shearing. Contamination of any component of the FRP system with an organic solvent may reduce tensile strength and other properties of the cured laminates.

C3.2.1 Safety Hazards

Consult Chapter 9 of ACI 503R-93 for additional information on safety hazards of epoxy. Ignition or fire in the proximity of epoxy resins could be hazardous. Appropriate references may be used for other types of resin such as vinyl esters. Placing carbon FRP sheets, bars, or strips near electrical equipment may cause short-circuit or electrical shock because carbon is a conductive material. Glass fibers are known to cause severe itching and skin irritation.

C3.2.2 Material Safety Data Sheets

The Code of Federal Regulations (CFR 16) regulates the labeling of hazardous substances and includes thermosetting-resin materials.

C3.2.3 Personnel and Workplace Protection

Safety measures may include protective clothing and devices (such as disposable plastic or rubber gloves, safety glasses or goggles, dust masks,
inform the personnel of the dangers of inhaling fumes of primer, putty, or resin and shall take all necessary precautions against injury to personnel. The resin mixing area shall be well vented to the outside.

3.3 Clean-Up

The contractor is responsible for the clean-up of the equipment and the project site from hazardous and aesthetically undesirable FRP components using appropriate solvents, as recommended in the system data sheet.

3.4 Disposal

Any component of the FRP system that has exceeded its shelf life or pot life or has not been properly stored, as specified in Section 3.1, and any unused or excess material that is deemed waste shall be disposed of in a manner amiable to the protection of the environment and consistent with the MSDS.

4 SUBSTRATE REPAIR AND SURFACE PREPARATION

The concrete substrate shall be repaired, if necessary, and all concrete surfaces shall be cleaned and prepared prior to installing the FRP system.

4.1 Removal of Defective Concrete

All defective areas of concrete substrate shall be removed according to ACI 546R-96 and ICRI No. 03730, using appropriate equipment such as an air- or electric-powered jack hammer or saw, at a sufficient depth of at least 12.7 mm (½ in.) beyond the repair area to expose sound aggregates. If any reinforcing or prestressing steel is exposed in the process and either it is deteriorated or its bond with the concrete is broken in the process, an additional nominal depth of 19 mm (⅞ in.) or at least 6.4 mm (¼ in.) larger than the largest aggregate in repair material shall be cut from its underneath. If any deterioration is noticed in the repair area, its source shall be located and treated to the satisfaction

safety gear respirators, fire extinguishers, and ventilators) depending on the FRP system, working conditions, and the job site. Disposable gloves may degrade in the presence of vinyl esters and solvents if not specifically designed for use with the FRP system.

C3.3 Clean-Up

The contractor may additionally consult with the prevailing environmental protection and health agencies for proper clean-up of the project site. Some clean-up solvents may be flammable.

C3.4 Disposal

Pot life depends on the system, mixed quantity, and ambient temperature. The contractor may also consult the prevailing environmental protection and health agencies for proper disposal of FRP components. Unused mixed primer, putty, or resin should be allowed to harden in their containers before disposal.

C4 SUBSTRATE REPAIR AND SURFACE PREPARATION

A clean and sound concrete substrate is essential to the effectiveness of the FRP system in achieving the design strength and the intended design objectives.

C4.1 Removal of Defective Concrete

Defects may include loose and broken debris or delaminated and spalled sections of concrete, voids and honeycombs, and deteriorated concrete. Defects in the concrete substrate can compromise the integrity of the FRP system. Any attempt at covering the deteriorated (carbonated or chloride contaminated) concrete with the FRP system without correcting the source of deterioration may be detrimental to the effectiveness of the repair. Investigations to date have shown that placement of externally bonded FRP, especially when used for full confinement, may arrest cracking of concrete and slow down the rate of corrosion of steel reinforcement, but does not stop or reverse the cor-
of the engineer prior to restoring the section. Upon removing defective concrete, and before restoring the section, the substrate shall be cleaned from any dust, laitance, grease, oil, curing compounds, impregnations, foreign particles, wax, and other bond-inhibiting materials, as per Section 4.4.6.

4.2 Repair of Defective Reinforcement

All defective reinforcement shall be repaired according to ICRI No. 03730 and to the satisfaction of the engineer. FRP systems shall not be applied to concrete suspected of containing corroded reinforcement. Corroded or otherwise defective reinforcement that is to be supplemented shall be cleaned and prepared thoroughly by abrasive cleaning to a near white appearance. Damaged reinforcement that needs to be replaced shall be cut at sufficient length, according to the contract documents and the approval of the engineer, to ensure full section and sound material in the remaining portion. Splice for the ruptured or cut reinforcing or prestressing steel shall be provided at sufficient length, according to the contract documents and approval of the engineer.

4.2.1 Mechanical Anchorage

Mechanical anchorage of the repair material with the substrate shall be placed if specified in the contract documents. Anchors shall be secured in place by tying to other secured bars and shall not protrude outside concrete surface. If that is not possible, the concrete surface shall be built up to cover the protrusions.

4.3 Restoration of Concrete Cross Section

The area of removed concrete substrate, and any void larger than 12.7 mm (1/2 in.) in diameter and depth, shall be filled with repair material that conforms to ICRI No. 03733. The repair material shall have a compressive strength equal to or greater than that of the original concrete, but no less than 31 and 38 MPa (4,500 and 5,500 psi) at 7 and 28 days, respectively. The design mix for all repair materials shall be approved by the engineer.

C4.2 Repair of Defective Reinforcement

Defects in the reinforcement may include section loss or rupture due to impact or corrosion. Any attempt at covering the deteriorated section with FRP without arresting the corrosion process may be detrimental to the entire repair because of the expansive forces associated with corrosion. If not treated properly, repair in one section may lead to an accelerated corrosion in an adjacent section. The exposed steel may be treated by applying corrosion inhibitors prior to restoring the section. The owner may require other treatment forms for corroded steel or placement of sensors to monitor the corrosion process. The splice detail is intended to provide strength and ductility in both longitudinal and transverse directions in case the FRP system is lost due to fire, vandalism, or any other cause.

C4.2.1 Mechanical Anchorage

Mechanical steel or plastic anchorage ensures adequate bond with the existing cross section, where new concrete patch material is placed. A grid of 102 mm × 102 mm (4 in. × 4 in.) with a minimum embedment depth of 38 mm (1 1/2 in.) is usually adequate. If the anchors protrude outside the concrete surface, they may damage fibers used in the FRP system.

C4.3 Restoration of Concrete Cross Section

The repair material may be an approved polymer- or latex-modified mortar/concrete or an approved factory-bagged mortar/concrete patching material of equal characteristics. It is recommended that the manufacturer be consulted on the compatibility of the repair material with the FRP system. At locations where the size of the voids or other constraints necessitate that prebagged mortar/concrete not be used, a Class III latex-modified concrete
The bond strength of the repair material to the existing concrete shall be a minimum of 1.4 MPa (200 psi) in the pull-off test according to ASTM D4541. The concrete substrate and the exposed reinforcing or prestressing steel shall be clean, sound, and free of surface moisture and frost before restoring the section. Before placement of patching materials, a water-based epoxy cementitious bonding agent shall be applied to concrete and exposed reinforcement. Also, cracks within solid concrete in the substrate shall be stabilized using epoxy injection methods, as specified in Section 4.4.3. If the water leak through cracks or concrete joints is significant, water protection and a water conveyance and weep holes shall be provided before restoring the section. The repair material shall be cured a minimum of 7 days before installing the FRP system unless its curing and strength are verified by tests.

4.4 Surface Preparation

All necessary repair and restoration of a concrete section shall be approved by the engineer prior to surface preparation. In these specifications, contact-critical applications are treated in the same way as bond-critical applications. An adhesive bond with adequate strength shall always be provided between FRP and concrete. Surface preparation shall also promote continuous intimate contact between FRP and concrete by providing a clean, smooth, and flat or convex surface. Surface preparation for near surface mounted FRP bars or strips is specified in Section 4.4.4. Surface preparation for FRP shell systems where grout is pumped into the gap between the shell and the existing column surface is specified in Section 4.4.5. All surface preparations shall be approved by the engineer before installing the FRP system.

4.4.1 Surface Grinding

All irregularities, unevenness, and sharp protrusions in the surface profile shall be ground away to a smooth surface with less than 0.8-mm (1/32-in.) deviation. Disk grinders or other similar devices shall be used to remove stain, paint, or any may be used, as approved by the engineer. No formwork is necessary for small voids, where repair materials may be placed by hand and troweled to match the original section. Formwork for larger areas may be built around the damaged area to ensure that the restored section is smooth and uniform and that it conforms to the original shape of the section. The instruction for most patching materials specifies a bonding agent, often a diluted mixture of the patching mix rubbed into the concrete. Curing time depends on the type of patching materials.

C4.4.1 Surface Grinding

Consult with the ACI 546R-96 and ICRI No. 03730 for grinding of concrete surfaces and for ensuring proper surface preparation. Vacuum cleaning could help reduce the dusts in environmentally sensitive areas.
other surface substance that may affect the bond. Voids or depressions with diameters larger than 12.7 mm (1/2 in.) or depths greater than 3.2 mm (1/8 in.), when measured from a 305-mm (12-in.) straight edge placed on the surface, shall be filled according to Section 4.4.5.

4.4.2 Chamfering Corners

All inside and outside corners and sharp edges shall be rounded or chamfered to a minimum radius of 12.7 mm (1/2 in.) as per ACI 440.2R-02. Ridges, form lines, and sharp or roughened edges greater than 6.4 mm (1/4 in.) shall need to be ground down or filled with putty, as specified in Section 4.4.5. Obstructions and embedded objects shall be removed before installing the FRP system if required by the engineer.

4.4.3 Crack Injection

All cracks in the surface of concrete or the substrate that are wider than 0.25 mm (1/100 in.) shall be filled using pressure injection of epoxy according to ACI 224.1R. Smaller cracks may also require resin injection in aggressive environments. Follow ACI 224R-01 crack width criteria for various exposure conditions. The FRP system shall be installed no earlier than 24 hours after crack injection. Any surface roughness caused by injection shall be removed as per Section 4.4.1.

C4.4.2 Chamfering Corners

Chamfering of corners improves the bond between FRP and concrete, reduces stress concentrations in the FRP, and helps prevent voids between the FRP and concrete [Yang et al. 2001a&b] (Figure C4.4.2). This is especially critical for carbon FRP systems because their transverse strength and modulus are substantially lower than their longitudinal values and, therefore, could easily fracture when bent over a sharp edge. Obstructions, reentrant corners, concave surfaces, and embedded objects can affect the performance of the FRP system.

Figure C4.4.2. Chamfering Corners

C4.4.3 Crack Injection

Movement of cracks wider than that specified may cause delamination or fiber crushing in externally bonded FRP systems. Crack injection helps restore concrete strength and prevent water leakage behind the FRP system. The procedure usually includes cleaning the cracks, sealing the surfaces, installing the entry and venting ports, mixing the epoxy, pressure injecting the epoxy, and removing the surface seal.
SPECIFICATIONS

4.4.4 Grooves for Near Surface Mounted FRP
A groove with dimensions specified in the contract documents shall be made in the concrete, where the FRP bar or strip is to be placed. Care shall be taken to avoid local fracture of the concrete surrounding the groove. The groove in which FRP is to be placed shall be free of loose, unsound, or bond-inhibiting materials such as oil, efflorescence, or moisture. All obstructions and embedded objects shall be removed from the groove area upon approval of the engineer.

4.4.5 Surface Profiling
After surface grinding, any remaining unevenness in the surface greater than that specified in Section 4.4.3, including out-of-plane variations, fins, protrusions, bug holes, depressions voids, and roughened corners, shall be filled and smoothed over using putty made of epoxy resin mortar or polymer cement mortar with strength equal to or greater than the strength of the original concrete. The patching material shall be cured a minimum of 7 days before installing the FRP system unless its curing and strength are verified by tests.

4.4.6 Surface Cleaning
Substrate concrete and finished surface of concrete shall be cleaned to the approval of the engineer. Cleaning shall remove any dust, laitance, grease, oil, curing compounds, wax, impregnations, stains, paint coatings, surface lubricants, foreign particles, weathered layers, or any other bond-inhibiting material. If power wash is used, the surface shall be allowed to dry thoroughly before installing the FRP system. The cleaned surface shall be protected against redeposit of any bond-inhibiting materials. Newly repaired or patched surfaces that have not cured a minimum of 7 days shall be coated with a water-based epoxy paint or other approved sealers.

5 INSTALLATION OF FRP SYSTEM
This section specifies general installation procedures for three types of FRP systems: wet lay-up, precured, and near surface mounted. Spe-

COMMENTARY

C4.4.4 Grooves for Near Surface Mounted FRP
It is recommended to first examine the existing conditions to assess the quality of the concrete substrate, identify potential obstructions, and verify the dimensions and geometries shown in the contract documents. The groove is often made using a grinder or concrete saw with a suitable blade. Embedded obstructions and objects can affect the performance of the FRP system.

C4.4.5 Surface Profiling
Consult the ACI546R and ICRI Guideline No. 03730 for surface profiling. Surface profile of the concrete substrate may provide an open roughened texture for precured FRP shell systems, where grout is pumped into the space between the shell and the existing column surface. Curing time depends on the type of patching materials.

C4.4.6 Surface Cleaning
This section relates to surface cleaning for the substrate after removal of defective concrete and prior to restoring the concrete section, as specified in Section 4.1. It also relates to surface cleaning of the finished surface of concrete before installing the FRP system. Cleaning may be performed with blast cleaning, an air blower, pressure washing, or other equivalent means. Clean wiping rags may also be used for removing any dust that may have been generated on the concrete surface during the grinding operation. Vacuum cleaning could help reduce the dusts in environmentally sensitive areas.

C5 INSTALLATION OF FRP SYSTEM
Contract documents provide specific procedures for the specific type of FRP system. Other, less common FRP systems, such as dry lay-up and
cific procedures for installing FRP systems may vary slightly for each system and manufacturer.

5.1 Environmental Conditions for Installation

Environmental conditions shall be examined before and during installation of the FRP system to ensure conformity to the contract documents and manufacturer’s recommendations. Do not apply primers, putty, saturating resins, or adhesives on cold, frozen, damp, or wet surfaces. Ambient and concrete surface temperatures shall be within 10–35°C (50–95°F), unless specified by the manufacturer. Moisture level on all contact surfaces shall be less than 10% at the time of installation of the FRP system, as evaluated according to ACI 503R-93. Moisture restrictions may be waived for resins that have been formulated for wet applications.

5.1.1 Moisture Vapor Transmission

Application of bonded FRP systems shall not proceed if any moisture vapor transmission is present. Concrete dryness is necessary when using elevated temperature cure. Any bubble that develops from moisture vapor transmission can effectively be injected with the same adhesive material used for the FRP system following the procedure specified in Section 7.2.

5.1.2 Applications in Inclement Weather

When inclement weather does not allow installation of the FRP system, as specified in Section 5.1, auxiliary measures may be employed to correct the conditions. An auxiliary heat source may be used in cold weather to raise the ambient and concrete surface temperatures to acceptable levels, as recommended by the manufacturer, but not higher than the glass transition temperature ($T_g$). Pressurized air may be used to dry the surface dampness.

5.2 Shoring

Repaired members shall be shored temporarily with conventional methods, if specified in machine-applied or automated, are not included in these specifications.

C5.1 Environmental Conditions for Installation

Moisture may hinder adhesion of the primer and resin. Work may be postponed if adverse weather, rain, or dew condensation is anticipated. Although moisture primarily affects the polymers and concrete surface, it may also collect on the surface of the fiber sheets if not stored properly, as specified in Section 3.1.1. Moisture on fiber sheets can cause problems with wet-out and cure of the system. Surface moisture may be measured using a mortar moisture meter or an absorbent paper. Cold weather may cause improper curing of the resin and saturation of fibers, compromising the integrity of the FRP system.

C5.1.1 Moisture Vapor Transmission

This section applies only to the conditions at the time of construction and not to those that should be addressed in the design process. Moisture vapor transmission from the concrete surface through uncured resin may cause air pockets and surface bubbles, compromising the bond between the FRP system and the concrete. These effects have primarily been observed in wet lay-ups, but are not excluded from other FRP systems.

C5.1.2 Applications in Inclement Weather

Different heating systems such as spotlights, electrical heaters, infrared heating, and heating blankets may be used. Electrical conductivity of carbon fibers may be used to apply a current, thereby providing fast in-situ curing in about 3 hours [CEB-FIP 2001]. The maximum elevated temperature depends on the system used. This procedure, however, is not yet widely accepted as providing a uniform and consistent cure profile.

C5.2 Shoring

In most applications, the FRP system may be applied while the structure is in service. Shoring
5.3 Equipment

The contractor shall provide all necessary equipment in sufficient quantities and in clean operating conditions for continuous uninterrupted FRP installation.

5.4 Application of Wet Lay-Up FRP Systems

This section specifies the necessary measures for installing wet lay-up systems using dry or prepreg fiber sheets and saturants.

5.4.1 Mixing of Resin Components

All resin components, including the main agent and hardener, shall be mixed at the proper temperature using the appropriate weight ratio and for a duration specified by the manufacturer until thorough mixing with uniform color and consistency is achieved. Resins shall not be diluted with any organic solvents such as thinner. Manual stirring and small electrically powered mixing blades are allowed. Resin shall be mixed in quantities sufficiently small to ensure that it can be used within its pot life. Any mixed resin that exceeds its pot life or begins to generate heat or show signs of increased viscosity shall not be used and shall be disposed of according to Section 3.4. Mixing of some resins may be accompanied by noxious fumes. Precautions must be taken, as specified in Section 3.2.1, regarding the resin’s impact on the environment, including emission of volatile organic compounds and toxicology.

5.4.2 Primer and Putty

A primer coat is generally required in all available FRP systems. Apply one or two coats of primer on the concrete surface to penetrate its open pores. Ambient and concrete surface temperatures must be within the range specified in Section 5.1. The putty, if used in the FRP system, shall be applied as soon as the primer becomes tack free or may be provided to either support the existing structure prior to repair or reduce the structure’s initial deflections prior to strengthening. Shoring may also be used to induce an initial camber in the system, thereby stressing the FRP system.

C5.3 Equipment

The equipment may vary for different FRP systems and may include resin impregnators, rollers, sprayers, and lifting and positioning devices.

C5.4 Application of Wet Lay-Up FRP Systems

Wet lay-up systems may alternatively be applied using special equipment (a saturator) to automate and speed up the process.

C5.4.1 Mixing of Resin Components

The term resin is a generic denomination used to identify all polymers employed in wet lay-up systems. Depending on its function, resin is more specifically identified as primer, putty, and saturant. Not all FRP systems use putty. Excessive agitation, when using electrically powered mixers, may cause froth and bubbles that can be entrapped as voids in the resin. Resin components are often contrasting colors; hence, full mixing is achieved when color streaks are eliminated. The stoichiometry of the resin will not be met unless resin solids at the bottom of the container are completely mixed. Pot life of resin depends on the resin type and the ambient temperature. Viscosity of a mixed resin that has exceeded its pot life will continue to increase, adversely affecting the resin’s ability to penetrate the concrete surface or saturate the fiber sheet.

C5.4.2 Primer and Putty

Primer may be applied using a clean roller or brush. The primer, when applied uniformly, helps hatch and strengthen the most external layer of concrete and improves the bond between the concrete substrate and the FRP system. The rate of surface coverage of primer is typically listed in the system data sheet. Not all FRP systems use putty.
SPECIFICATIONS

is not sticky to the fingers. The putty shall be applied within 7 days after primer application; otherwise, the primer-coated surface shall be roughened with sandpaper or a similar tool. The resulting surface shall be cleaned according to Section 4.4.6 before applying the putty. Apply a thin coat of putty in one or two layers, and smooth over the surface to fill in any small voids, cracks, or uneven areas. Any swelling on the surface after applying the putty shall be corrected to meet surface profile as specified in Section 4.4.5. The surfaces of primer and putty shall be protected from dust, moisture, and any other contaminants before applying the FRP.

5.4.3 Saturant

The first coat of saturating resin, saturant, shall be uniformly applied as an undercoat to all locations on the concrete surface where the FRP system is to be installed. The saturant shall have sufficiently low viscosity to ensure full impregnation of the fiber sheets prior to curing. To maintain proper viscosity of the saturant, the ambient and concrete surface temperatures must be within the range specified in Section 5.1. Any mixed saturant that exceeds its pot life shall be disposed of according to Section 3.4.

5.4.4 Applying Fiber Sheet and Saturant

Upon uniformly applying the first layer of saturant as an undercoat, the fiber sheet previously cut to the length specified in the contract documents shall be installed in place and gently pressed onto the wet saturant. Any entrapped air between the fiber sheet and the concrete surface shall be released or rolled across the sheet in the direction parallel to the fibers while allowing the resin to impregnate the fibers and achieve intimate contact with the substrate. Rolling perpendicular to the fiber direction is not allowed. In bidirectional fabrics, rolling shall be initially in the fill direction end to end and then in the warp direction. Sufficient saturant shall be applied on top of the fiber sheet, as overcoat, to ensure full saturation of the fibers. Undercoat, fiber sheets, and overcoat shall be applied with no interruption.

COMMENTARY

The primary function of the putty, if used, is to smoothen the concrete surface. The putty may be applied using a clean trowel or spatula or any other suitable tool. Adding silicate sand to the putty may improve stability and prevent swelling.

C5.4.3 Saturant

The resin that impregnates the fibers is the key component to form the FRP laminate that repairs or retrofits the concrete member. The rate of coverage of the resin is listed on the system data sheet, but generally depends on the type of resin, the ambient temperature, and the porosity of concrete surface. The typical rate of application is about 4.9 kg/m² (0.1 lb/ft²).

C5.4.4 Applying Fiber Sheet and Saturant

This installation procedure is for a single fiber sheet or the first fiber sheet or ply in a multiple-ply application. Alternatively, the fiber sheet may be separately impregnated using a resin-impregnating machine before being placed on the concrete surface. For ease of handling and to avoid wrinkling, fiber sheets are typically cut in segments shorter than 4.6- to 6.1-m (15- to 20-ft) lengths. Metal-serrated rollers are often used to force resin between fibers and to remove entrapped air. However, when used with excessive force, these rollers may cause fracture of the fibers. Rolling perpendicular to the fiber direction may misalign or damage the fibers.
5.4.5 Multiple-Fiber Plies

In multiple-ply installations, the sequence specified in Section 5.4.4 shall be repeated for each additional fiber sheet. The amount of resin overcoat for intermediate plies is approximately 15–20% greater than a single-ply installation because the saturant serves as overcoat for the applied ply and undercoat for the next ply. Follow the contract documents for the fiber orientation and ply stacking sequence. Each ply shall be applied before the onset of complete gelation of the previous layer. The number of plies that can be applied in a single day shall be based on the manufacturer’s recommendation and the approval of the engineer. Multiple plies can also be applied in several days. When previous layers are cured, interlayer surface preparation, such as light sanding and filling with putty, may be required, as specified in Section 5.4.2.

5.4.6 Overlapping

A lap joint shall be constructed when an interruption occurs in the direction of the fibers. The length of the lap splice shall be as specified by the contract documents, but must be at least 152 mm (6 in.). Staggering of lap splices on multiple plies and adjacent strips shall be required unless permitted by contract documents. No lap joint is necessary in the transverse direction unless specified in the contract documents.

5.4.7 Alignment of FRP Materials

The fiber plies shall be aligned on the structural member according to the contract documents. Any deviation in the alignment more than 5° (approximately 87 mm/m or 1 in./ft) is not acceptable, as specified in Section 6.3. Once installed, the fibers shall be free of kinks, folds, and waviness.

5.4.8 Anchoring of FRP Sheets

Anchoring of FRP sheets to the concrete substrate shall follow the method specified in the contract documents or approved by the engineer. When using mechanical clamps and fasteners, care
shall be taken to avoid damage to the FRP system or to the concrete substrate. Precautions shall be taken when steel fasteners are used for carbon FRP to avoid galvanic corrosion. FRP anchors shall be sufficiently embedded in concrete.

5.4.9 Stressing Applications
Stressing of FRP systems shall follow the method specified in contract documents. Active end anchorages shall be used for linear prestressing. For circular prestressing of wet lay-up systems, the gap left between the FRP system and the concrete column shall be filled using expansive mortar or pressure injection of epoxy grout, as specified in Section 5.5.4.

5.5 Application of Precured FRP Systems
Installation of precured FRP systems is generally similar to that of single-ply wet lay-up. Surface preparation of the concrete substrate shall provide an open roughened texture.

5.5.1 Application of Adhesive
Apply the adhesive uniformly onto all surface areas of the concrete substrate where the precured FRP system is to be installed. Thickness and viscosity of the adhesive layer shall be according to the manufacturer’s recommendations. Ambient and concrete surface temperatures must be within the range specified in Section 5.1 prior to applying the adhesive. Any mixed adhesive that exceeds its pot life shall be disposed of, as specified in Section 3.4.

5.5.2 Placement of Precured System
Precured FRP systems shall be cleaned, cut to the length specified in the contract documents, and placed into the wet adhesive within the pot life of the adhesive. Entrapped air between laminate and concrete shall be released, and excess adhesive shall be removed. Do not disturb the applied FRP system before the adhesive fully cures.

anchorage against premature delamination of the FRP system.

C5.4.9 Stressing Applications
Stressing and active confinement with a glass FRP system is NOT recommended because of concerns related to creep rupture. The prestrain in carbon should be limited to 50% of the ultimate strain due to damage tolerance concerns with unidirectional carbon FRP.

C5.5 Application of Precured FRP Systems
Precured FRP systems consist of laminates in the form of plates, strips, open grid forms, or shells. These systems are typically installed with an adhesive resin.

C5.5.1 Application of Adhesive
Adhesives may be applied with a spatula or any other suitable tool. The rate of coverage of the adhesive is listed on the system data sheet, but generally depends on the type of resin, the ambient temperature, and the porosity of concrete surface. The typical rate of application is about 4.9 kg/m² (0.1 lb/ft²). The adhesive is not necessary when an intentional gap is left between the concrete surface and the FRP shell to be later filled with grout, as specified in Section 5.5.4.

C5.5.2 Placement of Precured System
Since there are a number of different precured systems, it is important to follow the manufacturer’s recommendations on the timing and sequence of stacking, overlap and banding, horizontal and vertical joints, staggering of splices, and overlap and butt joints. The use of a dust mask is recommended when cutting precured FRP systems.
5.5.3 Anchoring of Precured System

Anchoring of precured systems is typically the same as anchoring for the FRP sheets, as specified in Section 5.4.8.

5.5.4 Grouting of Precured Shells

Precured shells around concrete columns shall be grouted no less than 24 hours after installation. Pressure grouting shall follow the contract documents and the manufacturer’s recommendations. The grout shall have a shrinkage strain of less than 0.0005 and a compressive strength greater than 27.6 MPa (4,000 psi).

5.5.5 Stressing Applications

Installation of prestressed FRP systems requires a moveable anchorage, which usually consists of gluing the FRP laminate termination between two steel plates held in place by screws. After curing the moveable anchorage, the fixed anchorage at the other end of the member shall be installed and the FRP laminate shall be glued between a steel plate and the concrete surface. Fasten the steel plate to the concrete surface using inserts. The fixed anchorage must be cured before the FRP laminate can be stressed. Install another fixed anchorage on the concrete surface at the other end of the member using an insert. Once the two fixed anchors have been installed, the system is ready for stressing with hydraulic jacks. During the prestressing process, an epoxy gel is spread uniformly on the entire concrete surface where the laminate has contact. The thickness of the epoxy gel shall follow the manufacturer’s recommendation. Any entrapped air shall be released by pressing on the FRP. After the epoxy gel has cured, the moveable anchor is removed and the laminate is cut. Both fixed anchors remain in place.

5.6 Application of Near Surface Mounted FRP Systems

Near surface mounted (NSM) FRP systems are an alternative to externally bonded FRP systems. In NSM systems, a bar or strip is inserted...
and anchored into a precut groove, as specified in Section 4.4.4. The NSM FRP system shall not be installed when surface moisture is present on the substrate or when rainfall or condensation is anticipated.

5.6.1 Application of Embedding Paste
Components of the embedding paste shall be mixed by the ratio specified by the manufacturer until thorough mixing with uniform color and consistency is achieved. All grooves, where the NSM FRP system is to be placed, shall be half filled with the paste. Ambient and concrete surface temperatures must be within the range specified in Section 5.1 prior to applying the paste. Mixed paste that exceeds its pot life shall be disposed of as specified in Section 3.4.

5.6.2 Placing FRP Reinforcement
The round FRP bar or rectangular FRP strip shall be cleaned, cut to the length specified in the contract documents, placed at mid-depth of the groove, and lightly pressed to force the paste to flow around it and completely fill the space between the FRP and the sides of the groove. The groove shall then be fully filled with additional paste, and the surface shall be leveled.

5.7 Curing
The FRP system shall be allowed to cure as recommended by the manufacturer. Field modification of resin chemistry for rapid curing is not allowed. Elevated cure temperature may be used, as specified in Section 5.1.2, if rapid curing is necessary. Cure of installed plies shall be monitored before placing subsequent plies. In case of any curing irregularity, installation of subsequent piles shall be halted. Unless otherwise noted in the contract documents and approved by the engineer, the full load shall not be applied until curing is complete. Protect the FRP system while curing, as specified in Section 5.9.

region without exposure to any potential mechanical or abrasion damage.

C5.6.1 Application of Embedding Paste
Any void that develops between concrete substrate and the embedding paste can be detrimental to the performance of the NSM FRP system.

C5.6.2 Placing FRP Reinforcement
FRP bars and strips may be cut with a high-speed grinding cutter or a fine blade saw. FRP bars or strips should not be sheared. The use of a dust mask is recommended when cutting FRP bars or strips. There are not yet sufficient data to support prestressing of NSM FRP systems.

C5.7 Curing
Curing is a time- and temperature-dependent process and may take several days in ambient temperature. In some FRP systems, pressure must be continuously applied through external means to prevent sag and pull-off during curing.
5.8 Protective Coating and Finishing
Protective coating shall be applied on the surface of the FRP system. The coating shall be a non-vapor-barrier, flexible, waterproofing, and compatible with the FRP system. The coating may be a polymer-modified Portland cement coating or a polymer-based latex coating. The mortar finish shall be made with silicate sand between sieves No. 40 (0.42 mm or \( \frac{1}{64} \) in.) and No. 6 (3.36 mm or \( \frac{1}{8} \) in.) and spread over the FRP system before the resin hardens. Appropriate methods shall be used for vertical or overhead work. The thickness of the coating shall be specified in the contract documents. Final appearance is to match, within reason, the color and texture of the adjacent concrete. Surface preparation shall be as recommended by the manufacturer. Solvent wipes shall not be used to clean the FRP surface unless approved by the FRP manufacturer. If abrasive cleaning is necessary, air pressure shall be limited to avoid any damage to fibers. Ambient and surface temperatures shall be within the range specified in Section 5.1 prior to applying the protective coating. Do not apply the coating when surface moisture is present or when rainfall or condensation is anticipated.

5.9 Temporary Protection
Temporary protection shall be installed, as specified in the contract documents, until the resin has fully cured, as approved by the engineer.

6 INSPECTION AND QA
All inspections and tests in this section will be performed by a trained inspector acting on behalf of the owner for QA of the project in the presence of the contractor and the engineer. The contractor may have its own inspector for QC.

6.1 Inspection of Materials
The manufacturer’s certifications for all delivered and stored FRP components will be inspected for conformity to the contract documents before starting the project. Materials testing will be...
conducted on samples of precured or NSM FRP or witness panels of wet lay-ups, if specified in the contract documents. Any material that does not meet the requirements of the contract documents will be rejected. Additional witness panels may be taken during the installation process if specified in the contract documents.

6.2 Daily Inspection
Daily inspection will include date and time of repair; ambient and concrete surface temperatures; relative humidity; general weather conditions; surface dryness per ACI 503.4; surface preparation and surface profile using ICRI surface profile chips; qualitative description of surface cleanliness; type of auxiliary heat source, if any; widths of cracks not injected with epoxy; fiber or precured laminate batch numbers and their locations in the structure; batch numbers, mixture ratios, mixing times, and qualitative descriptions of the appearance of all mixed resins, primers, putties, saturants, adhesives, and coatings; observations of the progress of the cure of resins; conformance with installation procedures; adhesion test results of bond strength, failure mode, and location; FRP properties from tests of field sample panels or witness panels, if required; location and size of any delaminations or air voids; and the general progress of work.

6.3 Inspection for Fiber Orientation
Fiber or ply orientation, fiber kinks, and waviness will be examined by visual inspection for conformity to the contract documents. Tolerances will follow Section 5.4.7. Nonconforming FRP area will be removed and repaired as per Section 7.4.

6.4 Inspection for Debonding
After at least 24 hours for the initial curing of the resin, a visual inspection of the surface will be performed for any swelling, bubbles, voids, or delaminations. If an air pocket is suspected, an acoustic tap test will be carried out with a hard object to identify delaminated areas by sound, with at least one strike per 0.1 m² (1 ft²). Defects smaller

extent of materials testing depends on the size and complexity of the project. Testing may include tensile strength and modulus, glass transition temperature \(T_g\), pot life, adhesive shear strength, lap splice strength, and hardness, according to ASTM standards, such as ASTM D3039.

C6.2 Daily Inspection
Consult ACI 440.2R-02 and the checklists in the accompanying process control manual for daily inspection and record keeping. The owner should retain the inspection records and witness panels for at least 10 years.

C6.3 Inspection for Fiber Orientation
See Section C5.4.7 for an explanation of the importance of fiber alignment and straightness.

C6.4 Inspection for Debonding
The inspector may look for changes in color, debonding, peeling, blistering, cracking, crazing, deflections, indications of reinforcing-bar corrosion, and other anomalies. Significance of debonding defects depends on the size, location, and quantity of the defects relative to the overall application area. Additional tests such as ultrasonic scanning [Littles
than 6.4 mm (¼ in.) in diameter will require no corrective action, unless as specified in Section 7.2. Defects larger than 6.4 mm (¼ in.) but smaller than 32 mm (1¼ in.) in diameter will be repaired as per Section 7.2. Defects larger than 32 mm (1¼ in.) but smaller than 152 mm (6 in.) in diameter, and with a frequency of less than 5 per any unit surface area of 3-m (10-ft) length or width, will be repaired as per Section 7.3. Larger defects will be repaired as per Section 7.4.

6.5 Inspection for Cure of Resin

If specified in the contract documents, the relative cure of resin in FRP systems will be examined by visual inspection or by laboratory testing of witness panels or resin-cup samples using ASTM D3418. Follow recommendations of the resin manufacturer for acceptance criteria. If the cure of resin is found unacceptable, the entire area will be marked and repaired as per Section 7.4.

6.6 Inspection for Adhesion

After at least 24 hours for the initial cure of the resin and before applying the protective coating, a direct pull-off test will be performed following ASTM D4541 to verify tensile bond between the FRP system and the concrete. Test locations and sampling frequency are as specified in the contract documents or as recommended by the contractor and approved by the engineer. At a minimum, three pull-off tests with at least one test per span or one test per 93 m² (1,000 ft²) of the FRP system, and one test per substrate concrete type, will be performed. Inspect the failure surface of the core specimen to ensure that the failure surface is by cohesive failure within concrete. Failure at the bond line at tensile stresses below 1.4 MPa (200 psi) is unacceptable. If one or more of the pull-off tests is found unacceptable, the work will be rejected and repair will follow Section 7.4. Repair cored areas as per Section 7.3.

6.7 Inspection for Cured Thickness

If specified in the contract documents or required by the engineer, 12.7-mm (½-in.) diam-
ter core samples will be taken to inspect the cured laminate thickness and the number of plies. Sampling frequency will be the same as is specified in Section 6.6 unless otherwise specified in the contract documents. Repair cored areas as per Section 7.3. The FRP system will be not acceptable if the number of plies is less than that specified in the contract documents or if the cured thickness of the FRP system is less than that specified in the contract documents by more than 0.8 mm (1/32 in). The entire area of the FRP system that is marked unacceptable will be repaired as per Section 7.4.

6.8 Load Tests

If specified in the contract documents, an in-situ conventional load testing will be conducted on the retrofitted structure.

6.9 Auxiliary Tests

If specified in the contract documents, auxiliary tests on witness panels will be carried out. The most common is the tensile test following ASTM D3039 on at least five witness panels for each type of FRP system to measure strength, elastic modulus, and ultimate strain. The measured thickness of the FRP laminate will also be recorded. The FRP system will be unacceptable if the average tensile strength and the lowest tensile strength are more than 5% and 10% below that specified in the contract documents, respectively.

7 REPAIR OF DEFECTIVE WORK

This section specifies the conditions and types of defects that require repair and the acceptable methods of repair. Defects are of different types and may be generally classified as aesthetic, short-term critical, or long-term critical. Repair procedure depends on the type, size, and extent of defects. Repair procedures for any condition not addressed in these specifications or in the contract documents shall be submitted by the contractor and approved by the engineer prior to proceeding with the work.

C6.8 Load Tests

The owner may anticipate in the contract documents a load rating of the structure upon completion of the project.

C6.9 Auxiliary Tests

The owner may anticipate in the contract documents additional tests for durability and accelerated aging of the FRP system with its protective coating against moisture, chemicals, and ultraviolet radiation. Other auxiliary tests may include interlaminar shear strength of FRP systems following ASTM D3165 or D3528.

C7 REPAIR OF DEFECTIVE WORK

Defects in FRP systems may include (1) voids and air encapsulation between concrete and layers of primer, resin, or adhesive and within the FRP system itself; (2) delaminations between layers of FRP system; (3) broken or damaged edges of the FRP system; (4) wrinkling and buckling of fiber and fiber tows; (5) discontinuities due to fracture of fibers, breakage in the fabric, or cracks in precured shells; (6) cracks, blisters, and peeling of the protective coating; (7) resin-starved areas or areas with nonuniform impregnation or wet-out; (8) undercured or incompletely cured resin; and (9) incorrect fiber orientation [Kaiser and Karbhari 2001a&b].
7.1 Repair of Protective Coating

Defects in protective coating can be of three types: small hairline cracks, blistering, and peeling. In all cases, moisture content of the substrate should be below 0.05% before applying a new coating. Prior to any repair of protective coating, the FRP system shall be examined visually or otherwise to ensure that no defect exists within or on the surface of the FRP. Defects in FRP, if found, shall be repaired as per Sections 7.2–7.4. If protective coating appears to show small areas with cracks, the local surface shall be lightly sanded. Then, a new coating with appropriate primer shall be applied according to the manufacturer’s recommendations. At the minimum, the coating shall be applied over an area extending 25 mm (1 in.) on either side of the defect. If the protective coating shows signs of blistering, the entire area of blisters as well as the surrounding area to a distance of at least 305 mm (12 in.) shall be carefully scraped clean. In no case should a blistered surface be recoated without complete removal of the existing coating. The area shall be wiped clean and then dried thoroughly. Once dry, the area can be recoated after application of the primer coat if required by the manufacturer. If the surface shows signs of excessive peeling, the entire coating shall be scraped off and the surface lightly sanded, wiped cleaned, and thoroughly dried before applying a new coat according to the manufacturer’s recommendations.

7.2 Epoxy Injection of Small Defects

Small entrapped voids or surface discontinuities no larger than 6.4 mm (1/4 in.) in diameter shall not be considered defects and require no corrective action unless they occur next to edges or when there are more than five such defects in an area of 0.9 m² (10 ft²). Small defects of size between 6.4 and 32 mm (1/4 and 1 3/4 in.) in diameter shall be repaired using low-pressure epoxy injection as long as the defect is local and does not extend through the complete thickness of the laminate in case of multiple-ply FRP systems. If any defects at edges or regions of discontinuity, no matter how small, can serve as stress risers that lead to rapid delaminations and growth of other types of defects. Care should be taken to ensure that the internal pressure caused between FRP layers due to injection does not cause further delaminations. Large disbonds close to the edge should not be injected but should be cut open and patched.
delamination growth is suspected between the FRP plies due to injection, the procedure shall be halted, and repair shall follow Section 7.3.

7.3 Patching of Minor Damages

Minor defects are those with diameters between 32 and 152 mm (1 1/4 and 6 in.) and a frequency of less than five per any unit surface area of 3-m (10-ft) length or width. The area surrounding the defects to an extent of at least 25 mm (1 in.) on all sides shall be carefully removed. The area shall be wiped clean and thoroughly dried. The area shall then be patched by adding an FRP patch of the same type as original laminate and extending at least 25 mm (1 in.) on all sides of the removed area. Repair can also be conducted using the procedure in Section 7.4.

7.4 Replacement of Large Defects

Defects larger than 152 mm (6 in.) in diameter shall be carefully marked and scarfed out extending to a minimum of 25 mm (1 in.) on all sides. Scarfing shall be progressive through the layers in the case of multiple-ply FRP systems until past the defective area. In case the defect extends to the first FRP ply adjacent to the concrete, the entire thickness of the FRP and primer shall be removed. The substrate shall be appropriately prepared and primer reapplied after ensuring that the surface and FRP are clean and dry. Application of a new FRP system within the scarfed area shall follow procedures for the original FRP system, except that an additional layer extending a minimum of 152 mm (6 in.) on all sides of the scarfed area shall be added as a patch. Once cured, the protective coating shall be applied over the entire area.

C7.3 Patching of Minor Damages

Minor damages to the FRP system may include cracking, abrasion, blemishes, chips, and cuts. The FRP patches should have the same characteristics (e.g., thickness, fiber orientation, ply stacking, and resin type) as the original laminate over the damaged area of which it will be bonded. Extending the FRP patch on all sides of the removed area helps with the load transfer.

C7.4 Replacement of Large Defects

Large defects are generally indications of significant debonding between layers, lack of adhesion to the concrete substrate, or extended moisture entrapment causing resin degradation. The defects may include peeling and debonding of large areas and nonlocal defects that may require full replacement. Large defects should be carefully examined, since they may be symptomatic of either significant short-term degradation or poor quality of materials or installation. If the extent of the defect is large and in areas critical to the structural integrity, it may be advisable to completely remove and reapply the entire FRP system.

8 MEASUREMENT AND PAYMENT

8.1 Method of Measurement

Measurement shall be taken as follows:

- Substrate repair, including removal of unsound concrete, sandblasting, cleaning of reinforcement and concrete, furnishing and placing new concrete, surface preparations, and all other incidentals by lump sum;

C8 MEASUREMENT AND PAYMENT

C8.1 Method of Measurement

For small projects, the substrate repair may be considered incidental to the FRP system. Often, upon removal of concrete, additional deteriorated areas may be delineated that warrant further undercutting and treating of the substrate or the reinforcement. The owner may require the contractor to
• Crack repair by epoxy injection by the linear meter (or linear foot) of the injected cracks;
• Furnishing and placing corrosion inhibitors by the square meter (or square foot) of concrete surface;
• Furnishing and placing the wet lay-up FRP system by the square meter (or square foot) of each layer applied;
• Furnishing and placing the precured FRP system by the square meter (or square foot) of each layer applied, accounting for different layer thicknesses;
• Furnishing and placing the near surface mounted FRP system by the linear meter (or linear foot) of each bar or strip; and
• Furnishing and placing the protective coating for the FRP system by the square meter (or square foot) of each layer of coating applied.

8.2 Basis of Payment

Payments shall be made as follows:
• Substrate repair as lump sum;
• Crack injection per linear meter (or linear foot);
• Furnishing and placing the corrosion inhibitors per square meter (or square foot);
• Furnishing and placing the wet lay-up FRP system per square meter (or square foot);
• Furnishing and placing the precured FRP system per square meter (or square foot);
• Furnishing and placing the near surface mounted FRP system per linear meter (or linear foot); and
• Furnishing and placing the protective coating per square meter (or square foot).

C8.2 Basis of Payment

For small projects, the substrate repair may be considered incidental to the pay item of the FRP system. The owner may also place limits on the substrate repair pay item by requiring the contractor to receive approval from the engineer on the limits of the removal area.
9 CITED REFERENCES