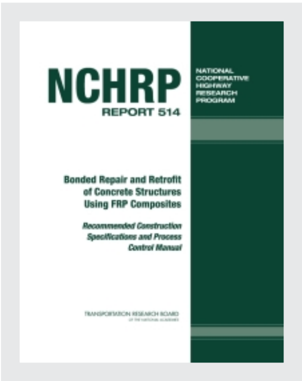

Bonded Repair and Retrofit of Concrete Structures Using FRP Composites -- Recommended Construction Specifications and Process Control Manual

DETAILS

0 pages | | PAPERBACK
ISBN 978-0-309-43205-4 | DOI 10.17226/22034

AUTHORS

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 514

Bonded Repair and Retrofit of Concrete Structures Using FRP Composites

Recommended Construction Specifications and Process Control Manual

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SUBJECT AREAS
Bridges, Other Structures, and Hydraulics and Hydrology

Research Sponsored by the American Association of State Highway and Transportation Officials
in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

WASHINGTON, D.C.
2004
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

Note: The Transportation Research Board of the National Academies, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

NCHRP REPORT 514

Project 10-59A FY'01

ISSN 0077-5614

ISBN 0-309-08785-6

Library of Congress Control Number 2003116851

Price $21.00

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 10-59 by the Constructed Facilities Laboratory, Department of Civil Engineering, North Carolina State University. SDR Engineering Consultants, Inc.; Co-Force America, Inc.; and Professor Vistasp Karbhari of the University of California, San Diego, were subconsultants to the North Carolina State University for this project.

Amir Mirmiran, Professor of Civil Engineering and Director of Technical Services at the Constructed Facilities Laboratory of the North Carolina State University, was the principal investigator. The other contributors to this document are Mohsen Shahawy, President, SDR Engineering Consultants, Inc.; Antonio Nanni, President, Co-Force America, Inc., and V&M Jones Chair Professor of Civil Engineering, University of Missouri, Rolla; and Vistasp Karbhari, Professor and Chair of Structural Engineering, University of California, San Diego.

FOREWORD

By David B. Beal
Staff Officer
Transportation Research Board

This report contains the findings of research performed to develop recommended construction specifications and a construction process control manual for bonded fiber reinforced polymer (FRP) repair and retrofit of concrete structures. The material in this report will be of immediate interest to bridge construction inspectors, general contractors, FRP subcontractors, and FRP and adhesive materials suppliers.

The long-term performance of bonded repairs and retrofits of concrete structures using FRP composites is very sensitive to the process by which the FRP material is stored, handled, mixed, applied, and cured. Because of the difficulty in quantifying the relationship between the long-term performance of FRP applications and the construction process, there has been no rational basis for construction specifications to ensure performance as designed.

DOTs have depended on composite materials manufacturers to provide construction process control. FRPs were developed for manufactured products, where processing could be tightly controlled. Many manufacturers prefer to have their own representatives provide construction process control. This arrangement has resulted in satisfactory outcomes, but it may not be practical as this technology moves into widespread use. The DOTs need to have some means, such as a process control manual, to check the constituent materials and the adequacy of the construction process.

The objective of this research was to develop recommended construction specifications and a construction process control manual for bonded FRP repair and retrofit of concrete structures to ensure performance as designed. This research was performed at the North Carolina State University with the assistance of SDR Engineering Consultants; Co-Force America, Inc.; and the University of California, San Diego. The report fully documents the research leading to the construction specifications and the process control manual. Generic quality assurance program checklists, which can be modified for specific projects, are provided in the attached diskette.

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SECTION II: Recommended Construction Specifications

SECTION III: Process Control Manual

SECTION I:

FINAL REPORT

BONDED REPAIR AND RETROFIT OF CONCRETE STRUCTURES USING FRP COMPOSITES

SUMMARY

Since its first applications in Europe and Japan in the 1980s, use of bonded repair and retrofit of concrete structures with fiber reinforced polymer (FRP) systems has progressively increased to the extent that today it counts for at least 25 Innovative Bridge Research and Construction (IBRC) projects in the United States, in addition to numerous projects independently undertaken by state departments of transportation (DOTs) and counties. Because of their light weight, ease of installation, minimal labor costs and site constraints, high strength-to-weight and stiffness-to-weight ratios, and durability, FRP repair systems can provide an economically viable alternative to traditional repair systems and materials. It is generally accepted that long-term performance of FRP systems is affected not only by the constituent materials, but also by the processes used during construction. However, the relationships between the long-term performance of FRP systems and the construction processes are not easy to quantify. Hence, there is a lack of generally accepted construction specifications and process control procedures for FRP repair systems, and state DOTs are heavily dependent on FRP manufacturers to provide construction process control. As the FRP technology matures and moves into widespread use, the need has become more urgent than ever to equip state DOTs with the means to specify and control the constituent materials and the adequacy of the construction process.

This study was undertaken to develop recommended construction specifications and a construction process control manual for bonded FRP repair and retrofit of concrete structures that will ensure performance as designed. The three most common types of FRP repair systems were considered: wet lay-up, precured, and near surface mounted. The study was based on then-current scientific and engineering knowledge, research findings, construction practice, performance data, and other information related to FRP constituent materials and FRP systems. The information was gathered from a literature search, existing databases, a questionnaire survey, telephone interviews, and a clearinghouse website. A number of issues and parameters relevant to FRP repair were identified based on the collected data and were used in developing the recommended construction specifications and the process control manual.

The proposed specifications include eight main sections: General; Submittals; Storage, Handling, and Disposal; Substrate Repair and Surface Preparation; Installation of

FRP System; Inspection and Quality Assurance; Repair of Defective Work; and Measurement and Payment. The proposed process control manual covers quality control (QC) and quality assurance (QA) prior to, during, and after completion of the repair project. It consists of planning, record keeping, inspection and QC tests. The manual includes the following main sections: QA Policy and Program Overview; QA Guidelines for Construction Activities; and Implementing and Monitoring of the QA Program. The manual also consists of a number of QA checklists for the FRP repair projects.

Critical review of the FRP research indicates a general consensus on the most relevant issues and parameters for construction specifications and a process control manual. However, the primary concern throughout this study has been, and remains, to justify the rational basis for the specified tolerances, criteria, and procedures. The novelty of the FRP technology and its subtle differences from the traditional repair systems are reflected in the proposed specifications. Some of the proposed provisions may appear more restrictive than the current practice for traditional materials. Although the industry may find such restrictions counterproductive for further development of new FRP technology, the main objective has been to help protect state DOTs from low-quality applications with major defects. The decision on relaxing or replacing any of the restrictions ultimately lies with the American Association of State Highway and Transportation Officials (AASHTO) and its member states. The states can use the proposed specifications and process control as "model documents" that need to be tailored to their specific needs as well as to the size and intent of each project. At the same time, it should be understood that as the FRP technology matures, and as new research data become available, some of those restrictions may be removed or relaxed. In fact, the report identifies provisions in the two documents that may need further refinement, and recommendations are made for future research to accomplish these refinements.

The long-term benefits of this research include lower maintenance costs and longer service life for repaired and retrofitted structures. These benefits will reduce the annual backlog for bridge replacement, resulting in lower costs to maintain or improve the transportation system. It is expected that bridge construction inspectors, general contractors, FRP subcontractors, and FRP and adhesive material suppliers will use the results of this research. Therefore, a four-element implementation plan is suggested for use by highway agencies. The plan includes training and technology transfer, a shakedown period, trial field applications, and an updating process.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

1.1 BACKGROUND

A significant portion of the U.S. highway infrastructure is in urgent need of strengthening and rehabilitation [*"The Status" 1993*]. It is vital to the state departments of transportation (DOTs) that innovative and cost-effective repair and retrofit systems be explored to extend service life and to improve performance of the highway infrastructure. Fiber reinforced polymer (FRP) systems have shown great potential for such applications. Currently, most FRP materials are made of continuous fibers of aramid FRP (AFRP), carbon FRP (CFRP), or glass FRP (GFRP) impregnated in a resin matrix. FRP materials can be fabricated into different shapes and forms, such as fabric, precured laminates and shells, and bars of different cross sections. FRP laminates have been used to replace bonded steel plates [*Sharif and Baluch 1996, Castro et al. 1996*], and FRP shells have been used as jackets for columns [*Seible and Innamorato 1995*]. The most important characteristics of FRP in repair and retrofit applications are the speed and ease of installation. Labor, shut-down costs, and site constraints typically offset the material costs of FRP, making the FRP repair systems very competitive with traditional techniques, such as steel plate bonding and section enlargement. FRP materials are durable, lightweight, and easy to install. They have very high strength-to-weight and stiffness-to-weight ratios and can be optimized for strength, stiffness, geometry, or durability in any environment. Potential disadvantages of FRP repair systems include cost, fatigue characteristics of glass fibers, low modulus of elasticity for glass and aramid fibers, long-term strength that could be lower than short-term static strength, and susceptibility to ultraviolet radiation damage.

FRP systems can be used either to rehabilitate and restore the strength of a weakened, damaged, or deteriorated structural member or to retrofit and strengthen a sound structural member to resist higher loads in case of a design or construction error, in case of a change in use or loading, or for a seismic upgrade. FRP materials can be used to provide increased shear and flexural capacity to structural components such as columns, beams, slabs and walls. They can strengthen bridges without reduction of vertical clearance, and they can be applied in a range of environmental conditions to alleviate environmentally induced deterioration. Typical applications include compensation for increased traffic volumes on bridges, dampening of vibration, corrosion rehabilitation, stress reduction in internal reinforcement, and repair of collision-damaged structures. The applications also include crack and spall controls.

Research on FRP materials for use in concrete structures began in Europe in the middle of the last century [*Rubinsky and Rubinsky 1954, Wines et al. 1966*]. The pioneering work of bonded FRP system can be credited to Meier [*Meier 1987*]; this work led to the first on-site repair by bonded FRP in Switzerland [*Meier and Kaiser 1991*]. Japan developed its first FRP applications for repair of concrete chimneys in the early 1980s [*ACI 440 1996*]. After the 1995 Hyogoken Nanbu Earthquake, Japan saw a surge in the use of FRP materials. By 1997, more than 1,500 concrete structures worldwide had been strengthened with externally bonded FRP materials. In the United States, field applications of FRP had a late start [*Goldstein 1996, GangaRao et al. 1997, Busel and Barno 1995*]. Currently, many state DOTs are actively pursuing the use of FRP for repair and retrofit of transportation structures. To date, more than 25 Innovative Bridge Research and Construction (IBRC) projects have been or are being conducted that involve the bonding of FRP composites to concrete structures [*Mertz et al. 2003*], in addition to numerous projects independently undertaken by state DOTs and counties [*Alkhrdaji et al. 2000, Mayo et al. 1999, Nanni et al. 2001, Schiebel et al. 2002, Shahawy and Beitelman 1996*].

The FRP technology is now relatively mature, with extensive research results on bond performance, creep effects, ductility of the repaired structure, fatigue performance, force transfer, peel stresses, resistance to fire, ultimate strength behavior, and design and analysis methods [*Mertz et al. 2003*]. It is widely accepted that quality of construction is one of the most important factors that affect long-term performance of FRP repair systems. Most FRP repair systems are deceptively simple to install. However, improper mixing of the resin components, saturating of the fibers, or misaligning of the fabric is not easily avoided without careful attention. Quality control (QC) is crucial to the successful application of FRP repair systems. The QC process should start before the system is installed and should continue through the installation. Selection of fiber type should be based on the strength, stiffness, and durability requirements of the specific application. Resins should be selected based on the environment that the FRP system will be exposed to, as well as the method by which the FRP system will be installed.

The acceptance and use of the FRP repair systems depend on the availability of clear design guidelines, installation procedures, and construction specifications [*Scalzi et al. 1999*]. Accordingly, a study was required to develop appropriate construction specifications and a process control manual for bonded repair and retrofit of concrete structures using FRP composites.

1.2 NCHRP PROJECT STATEMENT AND RESEARCH TASKS

To address the above concerns, the AASHTO-sponsored NCHRP developed a project statement to conduct NCHRP Project 10-59. The project statement, which was issued in summer 2000, reads as follows:

> There are no generally accepted construction specifications or process control procedures for bonded repair and retrofit of concrete structures using fiber-reinforced polymer (FRP) composites. The long-term performance of these applications is very sensitive to the process by which the FRP material is stored, handled, mixed, applied (including preparation of the underlying concrete surface), and cured. A finished FRP composite is characterized by both its constituent materials and the process by which those materials are formed into a composite. It is insufficient to characterize the composite by constituent materials only, as is commonly done. Assurance of as-designed properties is even more dependent on adequate process control in composites than it is in concrete. Because of the difficulty in quantifying the relationship between the long-term performance of FRP applications and the construction process, there has been no rational basis for construction specifications that will assure performance as designed.
>
> DOTs are generally dependent on composite materials manufacturers to provide construction process control. FRPs were developed for manufactured products, where processing could be tightly controlled. Many manufacturers prefer to have their own representatives provide construction process control, because guidelines and specifications are currently lacking. This arrangement has resulted in the most satisfactory outcomes, but it may not be practical as this technology moves into widespread use. The DOTs need to have some means, such as a process control manual, to check the constituent materials and the adequacy of the construction process.
>
> Bridge construction inspectors, general contractors, FRP subcontractors, and FRP and adhesive material suppliers will use the results of this research. The long-term benefits of this research include lower maintenance costs and longer service life for repaired and retrofitted structures. These benefits will reduce the annual backlog for bridge replacement, resulting in lower costs to maintain or improve the transportation system.
>
> The objective of this research is to develop recommended construction specifications and a construction process control manual for bonded FRP repair and retrofit of concrete structures to assure performance as designed. These documents will be prepared in a format suitable for consideration for adoption by the AASHTO Highway Subcommittee on Bridges and Structures.

The research tasks conducted under NCHRP Project 10-59 included the following:

1. Review and evaluate construction practice, performance data, research findings, and other information related to FRP constituent materials and FRP systems. Assemble this information from technical literature and from manufacturers' literature. In addition, assemble information from public agencies and private owners on their efforts to develop and use construction specifications for bonded FRP repair and retrofit of concrete structures.
2. Summarize the information collected in Task 1. This summary will include a discussion of relevant issues for each parameter to be included in construction specifications or a process control manual.
3. Prepare a detailed outline of construction specifications for the use of FRP for repair and retrofit of concrete structures. The outline shall include specific section titles and a discussion of relevant issues for each section.
4. Prepare a detailed outline of a process control manual. This outline shall include construction record keeping and quality assurance (QA) procedures for bonded FRP applications on concrete structures. These procedures shall include recommendations for test equipment, inspection and test methods, and acceptance limits for test results.
5. Submit an interim report, within 6 months of contract start date, documenting the findings of Tasks 1 through 4. Include an expanded work plan for the remainder of the project. The contractor will be expected to meet with the NCHRP project panel approximately 1 month later. Work shall not proceed on Tasks 6 through 11 until the approval of the expanded work plan by NCHRP.
6. Expand the approved outline for the construction specifications to a full draft document with commentary.
7. Expand the approved outline for the process control manual to a full draft document.
8. Submit the drafts of the construction specifications and the process control manual to NCHRP not later than 8 months after the approval of the Task 5 work plan. Meet with the NCHRP project panel approximately 1 month later.
9. Revise the draft construction specifications and process control manual in accordance with the NCHRP review comments.
10. Identify provisions in the construction specifications and process control manual that may need further refinement. Prepare recommendations for a possible Phase II of this project to accomplish these refinements. These recommendations should include a testing and monitoring program to determine the long-term effectiveness of bonded FRP applications on concrete struc-

tures using the construction specifications and process control manual.

11. Prepare a report summarizing the research. The recommended construction specifications and process control manual shall be submitted as stand-alone documents.

1.3 RESEARCH APPROACH AND DELIVERABLES

NCHRP Project 10-59 developed two separate stand-alone documents: *Construction Specifications and Commentary* and *Process Control Manual*. These documents are intended for possible adoption by the AASHTO Highway Subcommittee on Bridges and Structures. During the course of the project, first an outline for each document was developed based on a thorough review of published and unpublished literature; a questionnaire survey of state DOTs, academic institutions, contractors, and suppliers; existing specifications of the manufacturers and state DOTs; and a detailed assessment of the relevant issues and parameters. The outlines were included as part of the interim report, which was reviewed by the NCHRP Project Panel C10-59. Subsequently, a preliminary draft and a revised draft of each document were prepared for and reviewed by the panel.

The project was intended to incorporate then-current research findings, construction practices, performance data, and other information related to FRP constituent materials and FRP systems. During the course of the project, and as stipulated in one of the tasks, knowledge gaps were identified for some of the provisions in the two documents. Recommendations were made for necessary refinements of the documents in those areas.

1.4 APPLICABILITY OF RESULTS TO HIGHWAY PRACTICE

Recently, *NCHRP Report 503: Application of Fiber Reinforced Polymer Composites to the Highway Infrastructure* identified retrofitting of concrete components as the most promising application of FRP materials to the highway infrastructure [*Mertz et al. 2003*]. The results of this investigation therefore immediately apply to the highway construction practice. The results fill the gap that currently exists for the use of FRP materials and will relieve DOTs from their sole dependence on manufacturers of FRP materials to provide construction process control. The results are expected to help move the rather new FRP repair technology into widespread use for DOTs. The outcomes of the project will equip the DOTs with the necessary means to control the application of the repair system and the adequacy of the construction process. The results can be equally used by bridge construction inspectors, general contractors, FRP subcontractors, and FRP and adhesive material suppliers. The long-term benefits of this research will include lower maintenance costs and longer service lives for repaired and retrofitted structures. These benefits will reduce the annual backlog for bridge replacement, resulting in lower costs to maintain or improve the transportation system. Considering the distinct differences between the FRP repair systems and the current practice, there will be a need to educate and train construction engineers on the use of the new materials and the new provisions.

1.5 SECTION I ORGANIZATION

This section provides a summary of the work conducted under NCHRP Project 10-59. The specific construction provisions were submitted to NCHRP in two separate documents: *Recommended Construction Specifications* and *Process Control Manual*. These documents are included as Sections II and III, respectively, in this report. Chapter 1 of this section (this chapter) provides an overview of the project background and objectives. Chapter 2 describes the data collection and evaluation of construction practice, performance data, research findings, and other information related to FRP constituent materials and FRP systems. Chapter 3 provides a review and discussion of some of the relevant technical issues and parameters that were included in the recommended construction specifications and the process control manual. Also, the outline and contents of the two documents, along with the philosophy behind their development, are discussed. Chapter 4 presents a summary of this report, recommendations for a possible Phase II of this project, and suggestions for implementing the results of this research.

CHAPTER **2**

FINDINGS

2.1 DATA COLLECTION AND EVALUATION

A database was compiled of the information on construction practice, field and laboratory performance data, research findings, constituent materials and FRP systems, and evaluation and inspection methods. The information was gathered from online and catalog searches of literature in science and technology databases; the available data at the National Science Foundation (NSF) Industry–University Center on Repair of Buildings and Bridges with Composites at the University of Missouri-Rolla and the North Carolina State University; the questionnaire survey of state DOTs, academic institutions, contractors, and suppliers; telephone interviews with selected state DOT maintenance engineers, contractors, composites suppliers, and materials experts; and a clearinghouse website at the North Carolina State University to allow further input to the project throughout its duration.

2.1.1 Questionnaire Survey

A questionnaire survey was distributed to all state DOT bridge engineers, state representatives for the Transportation Research Board (TRB), nonvoting members of AASHTO, members of the American Concrete Institute (ACI) Committee 440 on FRP Reinforcement, FRP composites industry, and industry and academics in the overseas. The respondents included 27 state DOTs, 2 Canadian provinces, 5 manufacturers and suppliers, and 3 universities. Four of the responding state DOTs (Louisiana, Montana, North Dakota, and Virginia) and the two Canadian provinces (Ontario and Saskatchewan) indicated lack of prior experience with FRP. The others, however, provided valuable information on relevant issues and parameters for construction specifications and a process control manual. The relevant issues are outlined in Section 2.2. A detailed discussion of the relevant issues and the associated parameters is presented in Chapter 3. Some state DOTs and manufacturers provided their current specifications, as discussed in the next section.

2.1.2 Current Specifications

Fourteen state DOTs (California, Hawaii, Illinois, Indiana, Maryland, Michigan, Minnesota, Nevada, New Hampshire, New York, Oklahoma, Texas, Utah, and Washington) provided sample specifications from their recent FRP repair projects. Most of these projects were funded as part of the Transportation Equity Act for the 21st Century (TEA-21). TEA-21 established the IBRC program, which provides funding to help state DOTs and local and county road agencies defray the cost of incorporating innovative materials and technologies in bridge construction. While most of these specifications are only for column-wrapping projects, they still provide insight into the current use of FRP specifications by the state DOTs. Some of these specifications are modified versions of the manufacturers' specifications that are placed in contract documents. Some states provide alternative schemes, referring to different FRP repair systems from different manufacturers. The format of these specifications generally follows that of the Construction Specification Institute (CSI).

In addition to the state DOTs, specifications and QC documents were obtained from a number of manufacturers. These specifications, although material specific and product specific, provide a good framework for model specifications.

2.1.3 Relevant Documents

The following documents were found relevant to this investigation.

The ACI Committee 440 has developed a guide [*ACI 440 2002*] for the design and construction of externally bonded FRP systems for strengthening concrete structures. Part 3 of the document covers recommended construction requirements, including shipping, storage, handling, installation, inspection, evaluation, acceptance, maintenance, and repair. Some of the issues covered under installation include contractor competency, temperature, humidity, moisture, equipment, substrate repair, surface preparation, mixing of resins, application of constituent materials, alignment of FRP materials, multiple plies and lap splices, curing of resins, and temporary protection.

The International Conference of Building Officials (ICBO) has developed two acceptance criteria documents (see www.icbo.org): *AC 125* for strengthening of concrete and reinforced and unreinforced masonry with FRP and *AC 78* for inspection and verification of such strengthening. These criteria documents establish minimum requirements for the issuance of ICBO evaluation reports on FRP systems for strengthening. The qualification test plan in *AC 125* includes testing of columns (flexure and shear), beam-to-column joints, beams (flexure and shear), walls (out-of-plane flexure and in-plane shear), wall-to-floor joints, slabs (flexure), physical and mechanical properties of FRP composite materials, exterior exposure, freezing and thawing, aging, alkali soil resistance, fire-resistant construction, interior finish, fuel resistance, adhesive lap strength, and bond strength. The inspection and QC aspects are discussed in more detail in *AC 78*.

The Highway Innovative Technology Evaluation Center (HITEC), formed by the Civil Engineering Research Foundation (CERF), is charged with facilitating the introduction of new technology in the highway infrastructure. HITEC has developed an evaluation plan for FRP repair systems [*Reynaud et al. 1999, HITEC 2001*]. The plan identifies several issues for FRP repair systems. They include methods of preparation of concrete substrate; the ensuring of appropriate impregnation of fabric and compaction of impregnated fabric once placed on concrete substrate; control over thickness of adhesive bondline; a method of ensuring appropriateness of design, especially as related to materials durability and level of performance of the unstrengthened system; methods on QC/QA to be used during field construction and application; and training and qualification of applicators. The plan also discusses issues related to inspection, maintenance, and monitoring of FRP repair systems. The issues include methods of inspection during construction and application, the need for a field inspection manual for resident engineers and inspectors, the need for periodic inspection, the development of nondestructive evaluation (NDE) test methods for routine monitoring and structural health inspection with criteria for identification of system performance, methods for routine maintenance and development of specifications to classify type of maintenance to be conducted, and methods to evaluate soundness of composite-concrete bond and overall durability of the system in the field. The plan further addresses the need for a minimum of three semiannual periodic field inspections of one repair site per participating state DOT using several techniques, including pull-off testing on the concrete and composite bonded to concrete; determination of glass transition temperature of the composite through the dynamic mechanical thermal analysis; determination of moisture content through appropriate thermal techniques; and visual inspection for signs of peel, cracking, and other distress. Finally, the plan calls for modal testing analysis of the repaired or strengthened bridge as an NDE tool.

CERF has recently published a document on the gap analysis for durability of FRP composites in civil infrastructure [*CERF 2001*]. The document states that since FRP composites are still relatively unknown to the practicing civil engineer and infrastructure systems planner, there are heightened concerns related to the composites' overall durability, especially as related to their capacity for sustained performance under harsh and changing environmental conditions under load. The lack of an easily accessible and comprehensive database on these materials makes it difficult to specify FRP composites for construction. The lack, or inaccessibility, of data related to the durability of these materials is proving to be one of the major challenges that need to be addressed prior to the widespread acceptance and implementation of these materials in civil infrastructure. The CERF report provides the results of a "gap analysis" to identify critical areas in which data are needed as related to specific applications.

The Navy Pier Life Extension Program's Advanced Technology Demonstration Sites has provided three site-specific reports on repair and upgrade of waterfront structures and piers. The first report regarding Pier 11 in Norfolk, Virginia [*Warren 1997*], provides a detailed account of the design of a graphite reinforced epoxy laminate composite overlay for the underside of the deck, preparation of the concrete surface, installation of the upgrade overlay, installation of monitoring sensors, and a load assessment of the upgraded deck slab. The second report regarding Pier 12 in San Diego, California [*Warren 1998*], details the methodology of upgrading using external carbon/epoxy composite reinforcing and includes specifications. The third report regarding Bravo 25 in Pearl Harbor, Hawaii [*Warren 2000*], discusses concrete repair and rehabilitation, an impressed current cathodic protection system, and carbon/epoxy composite external reinforcement. Although the specifications and QA tests are quite extensive, they are material specific and project specific.

The International Concrete Repair Institute (ICRI) has several guides for repair of concrete structures, including ICRI 03730 and ICRI 03733. ICRI and ACI have published *Concrete Repair Manual* [*ICRI/ACI 1999*], which consists of evaluation (condition survey, nondestructive testing, laboratory investigation, and causes of deterioration and distress), repair materials and methods, execution (material selection, selection of application method, plans and specifications, concrete removal, surface preparation, and QC/QA), protection and maintenance (surface treatments, joint sealants, cathodic protection, and cleaning), structural strengthening, and specific considerations and case studies (bridges, dams, other hydraulic structures, and pavement and parking lots). Most specifically, the useful specifications and guides in the manual include *Guide for Evaluation of Concrete Structures Prior to Rehabilitation (364.1R)*, *Use of Epoxy Compounds with Concrete (503R)*, *Standard Specification for Repairing Concrete with Epoxy Mortars (503.4)*, and *Concrete Repair Guide (546R)*.

The Canadian Network of Centers of Excellence on Intelligent Sensing for Innovative Structures (ISIS Canada) has published a comprehensive manual on FRP repair systems for concrete structures [*ISIS Canada 2002*]. The document includes design guides, typical specifications, and QC/QA plans. The typical specifications include approval of FRP materials (descriptive and performance specifications by the engineer and specifications by the contractor); handling and storage of FRP; staff qualifications; concrete surface preparation for flexural, shear, or confinement application in dry or other particular conditions; installation of FRP systems regarding preparation and climatic conditions (equipment, temperature, humidity, and mixing of resins); general installation procedures (primer and putty, hand-applied wet lay-up systems); particular installation procedures (precured systems, alignment of FRP materials, multiple plies and lap joints);

cure; protection; and finishing. The QC/QA plans include materials qualification and acceptance, qualification of contractor personnel, inspection of concrete substrate, FRP material inspection (before construction, during construction, and at completion of the project, regarding delaminations, cure of systems, adhesion, laminate thickness, and material properties), qualification testing, and field testing.

The International Federation for Structural Concrete (FIB—Fédération Internationale du Béton) Task Group 9.3 on *FRP Reinforcement for Concrete Structures* was convened in 1993 to establish design and construction guidelines based on the format of the Comité Euro-International du Béton (CEB) and Fédération Internationale de la Précontrainte (FIP) model code and Eurocode 2. The subgroup on externally bonded reinforcement has published a technical report on externally bonded FRP repair systems [*CEB-FIP 2001*]. This document contains a chapter on practical execution and QC, in which it addresses the basic technique involving three acting elements: substrate, adhesive/resin, and FRP reinforcement. The report identifies two major types of FRP repair systems: (1) wet or hand lay-up and (2) prefabricated or precured strips or laminates. The report then outlines the general requirements before application of FRP system. It also provides a flow chart for FRP applications. The extended section on QC covers

- Physical properties of bonding agent (viscosity and thixotropy, curing conditions and shrinkage, pot life, open time and shelf life, glass transition temperature, moisture resistance, and filler properties);
- Short-term mechanical properties of cured adhesive (modulus of elasticity in flexure, shear strength, adhesion strength, and compressive strength);
- Durability and long-term properties of cured adhesive (accelerated laboratory testing and long-term, 15-year performance);
- Physical properties of FRP systems (fiber fraction, amount of resin for impregnation, coefficient of thermal expansion, glass transition temperature, moisture absorption, and chemical stability);
- Short-term mechanical properties of FRP systems (tensile strength, elastic modulus, and tensile failure strain);
- Durability and long-term properties of FRP systems (moisture, chemicals, and ultraviolet radiation); and
- The composite action among FRP system, bonding agent, and concrete (applicability test, bond performance in direct tension, durability testing, and bond performance in shear).

The document also covers QC issues, such as

- Qualification of workers,
- QC plan,
- QC of the supplied materials (representative samples and independent certifications),
- QC on the application conditions (concrete quality: tensile strength of concrete surface by pull-off test, unevenness of repaired concrete surface, ambient humidity and temperature, surface moisture and temperature),
- QC on the application process (substrate repair, surface preparation, resin mixing, and bond interface),
- QC after application with partially destructive techniques (surface adherence pull-off test, surface adherence shear test, and surface adherence torque test), and
- Nondestructive techniques (tapping, ultrasonic pulsed echo techniques, ultrasonic transparency techniques, thermography, and other dynamic methods such as impact spectrum analysis or acoustic wave propagation).

The concrete society committee in the United Kingdom has published a technical report on strengthening of concrete structures using FRP composites [*TCS 2000*]. The document reviews pertinent material types and properties, as well as applications and details on design, construction quality, and long-term inspection and monitoring. Separate chapters address details related to the design of members in flexure and shear, as well as confinement of columns. Specific sections consider the use of partial safety factors based on material in the ultimate state and manufacturing method. There is a special chapter on workmanship and installation that provides details on methods for the evaluation of the concrete substrate and preparation of the surface for bonding. Details related to the importance of materials inspection, mixing and application of adhesive, and inspection procedures are provided. In addition, there is a special section on the preparation and use of control samples to characterize properties of materials used. The use and application of protective coatings is also elucidated, as is the need for having warning signs to prevent accidental damage to the composites through construction procedures after external FRP bonding. A special chapter outlines the need and proposed methodology for long-term inspection and monitoring, emphasizing the use of additional composite samples to be bonded to the substrate to enable pull-off tests over periods of time.

The Japan Society of Civil Engineers (JSCE) has published recommendations for design and construction of concrete structures using continuous fiber reinforcing materials [*JSCE 1997*, *JSCE 2001*]. The documents, which are intended for concrete structures other than buildings, cover quality specifications and test methods for FRP materials. The quality requirements of both fiber and binder materials are addressed. Also, mechanical properties for various types of fiber reinforcement systems are discussed, including fiber volume ratio, reinforcement cross-sectional area, guaranteed tensile strength, tensile modulus, elongation, creep rupture strength, relaxation rate, and durability. For each specified property, a particular test method is prescribed in the document. The document, however, does not have the format of construction specifications.

The Japan Concrete Institute (JCI) published a technical report on the use of FRP composites for concrete structures [*JCI 1998*]. The report primarily focuses on the application of fabric sheets using the wet lay-up process and details methods and procedures for testing and validation of material properties and for life-cycle assessment. Many of the tests are aimed at both the initial characterization of the material and the validation of design properties. Details related to test protocol, devices to be used, and procedures for calculation and presentation of results to enable comparison are presented. Special sections are devoted to construction methods and improvements needed within them for purposes of QC, as well as the training of technicians.

2.1.4 Relevant Projects

Three other NCHRP projects relate to the FRP materials: Project 10-55, "Fiber Reinforced Polymer Composites for Concrete Bridge Deck Reinforcement"; Project 10-64, "Field Inspection of In-Service FRP Bridge Decks"; and Project 4-27, "Application of Fiber Reinforced Polymer (FRP) Composites to the Highway Infrastructure: Strategic Plan." The first two concern new construction with FRP. Project 4-27 has identified bonded repair and retrofit of concrete as one of the most promising near-term applications of FRP in highway infrastructure [*Mertz et al. 2003*]. It also conducted a survey questionnaire of the state DOTs. Of the 23 responses that were received, 11 state DOTs (California, Idaho, Kansas, Massachusetts, Minnesota, Missouri, Nevada, Oregon, South Carolina, Tennessee, and Utah) cited prior use of FRP for repair and retrofit of concrete structures. Eighteen FRP repair or strengthening projects were documented, of which three projects related to seismic retrofit. Of the responses, six state DOTs (California, Nevada, New Hampshire, Oregon, Texas, and Utah) reported having their own construction/installation specifications for FRP applications. Oregon and Utah also reported having their own design specifications for FRP applications.

FHWA has two projects related to the specifications for FRP materials: one for materials specifications and another for design and construction specifications.

The first FHWA project, titled "Specifications for FRP Highway Bridge Applications," was carried out at the University of Wisconsin-Madison [*Bank et al. 2002*]. The project has developed a model specification for FRP composite materials for use in civil engineering structural systems. The model specification provides a classification system for FRP materials, describes admissible constituent materials, and specifies limits on selected constituent volumes. The model specifications cover the following subjects: scope, classification, constituent materials, testing, terminology, ordering, sampling, certification, marking, packaging, reporting, and QA. Test methods permitted for obtaining mechanical and physical properties are detailed, and limiting values for selected properties in the as-produced state and in a saturated state are stipulated. The project has also outlined a protocol for predicting long-term property values subjected to accelerated aging.

The second FHWA project, titled "Construction Specifications and Inspection Process for FRP Repair/Strengthening of Concrete Structures," is underway at the University of Missouri-Rolla. It focuses on the validation experiments leading to construction specifications and inspection process. The project aims at developing model construction specifications and criteria for field inspection for use by FHWA and AASHTO. Testing and verification in both the laboratory and the field are being conducted to develop the database for the specifications. The goal is to identify the construction procedures that ensure long-term performance for FRP repair and retrofit systems bonded to concrete structural elements. The project intends to develop a model to predict the long-term performance of FRP systems using short-duration (i.e., accelerated) test methods. Table 2.1 outlines the topics that are covered in the FHWA project as they relate to externally bonded sheets, prefabricated laminates, durability of FRP repair, end anchorage, and near surface mounted FRP. The project also covers topics related to repair and retrofit with external posttensioned FRP. Preliminary findings of the project have been reported in the published literature [*Belarbi et al. 2002, De Lorenzis and Nanni 2002, De Lorenzis et al. 2001, De Lorenzis and Nanni 2001, Galecki et al. 2001, Hughes et al. 2001, Maerz et al. 2001a&b, Micelli et al. 2002, Murthy et al. 2002, Shen et al. 2002, Yang et al. 2001a&b, Yang et al. 2002, Yang and Nanni 2002*].

A number of state DOTs have contracted several research projects to universities to develop guidelines and model specifications. Oregon DOT, for example, has contracted the University of California, San Diego, to develop a synopsis for the quality and monitoring of structural rehabilitation measures [*Kaiser and Karbhari 2001a&b*]. Michigan DOT has also contracted the University of Michigan to carry out research and develop model specifications for FRP repair systems [*Naaman 1999*].

2.2 RELEVANT ISSUES

Issues that relate to the construction specifications and to the process control manual were identified during the assessment of the collected data. These issues are outlined in the following sections and discussed in detail in Chapter 3.

2.2.1 Construction Specifications

The relevant issues can be categorized into the following areas:

- Scope of the specifications
- Construction tolerances
- Fire considerations
- Project submittals
- QC/QA
- Qualifications for FRP system, manufacturer/supplier, and contractor/applicator
- Storage and handling
  - Preservation of material properties
  - Shelf life and pot life

TABLE 2.1 Research topics of FHWA/University of Missouri-Rolla project on FRP repair systems

Area	Topic	Subtopic
Externally Bonded Sheets and Prefabricated Laminates	Substrate Condition	Surface Profile
		Surface Strength
		Intimate Contact
		Presence of Moisture or Frost
		Moisture Vapor Transmission
		Crack Injection
		Moving Cracks
	Materials and Material Handling	Dust Control
		Fiber Irregularities
		Storage
	Installation	Epoxied Surface Smoothness
		Unattended Epoxy Surfaces
		Fiber Alignment
		Voids/Delaminations
		Cure Time Limits
		Corner Radius
		FRP Strip Spacing
		Bonded Length
		Lap Splice Length
	Inspection Devices and Methods	Surface Roughness Test
		Pull-Off Test (Bond)
		Torque Test (Bond)
		Voids/Delaminations Test
Durability of FRP Repair	Aggressive Environment	Freeze-Thaw Cycles
		Extreme Thermal Gradients (Nonfreeze)
		UV Exposure
		Relative Humidity
		Long-Term Exposure to Salts
End Anchorage	Installation Purpose	Shear Strengthening
		Flexural Strengthening
	Anchor Details	Groove Dimensions
		Type of FRP Bar
Near Surface Mounted FRP	Substrate Condition	Surface Preparation
	Materials and Material Handling	Type of FRP
	Installation	Dimensions of Groove
	Inspection Devices and Methods	N/A

- Safety issues
  - Material safety data sheet (MSDS)
  - Work place and personnel safety
  - Disposal and cleanup
- Repair of the substrate
  - Types of defects in concrete and reinforcement
  - Repair procedure and steps for concrete and reinforcement
  - Surface preparation
  - Tolerances for grinding
  - Tolerances for corner radius
  - Bond-critical versus contact-critical applications
- FRP repair systems
  - Types of FRP repair systems: wet lay-ups, precured, and near surface mounted
  - Environmental conditions for applications
  - Application procedures and steps
  - Protective systems
  - Stressing applications and creep rupture
- Inspection
  - Methods of inspection
  - Items for inspection
  - Sampling frequency and location
  - Acceptance criteria
  - Record keeping
- Repair of defective work
  - Type and size of defects
  - Methods of repair
  - Acceptability of defect and repair
- Measurement and payment

2.2.2 Process Control Manual

The relevant issues can be categorized into the following areas:

- QA policy
- QA responsibilities
- Elements of the QA plan
- QA procedures and checklists
- Record keeping
- Implementation

CHAPTER 3

INTERPRETATION, APPRAISAL AND APPLICATIONS

3.1 GENERAL ISSUES

The scope of the project was limited to the construction of bonded repair and retrofit of concrete structures using FRP composites. Therefore, issues of design and periodical inspection and maintenance were not considered. Moreover, nonbonded applications such as external posttensioning were not considered.

Three sets of information are considered necessary prior to the start of any FRP repair project: working (shop) drawings, a QC/QA plan, and qualifications. The purpose of working drawings is to identify all necessary details about the project, the type of FRP system, and the work plan. The QC/QA plan should 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 to specifications, QA samples, inspection of all completed work (including necessary tests for approval), repair of any defective work, and clean-up. Quite appropriately, the level of QC and the scope of testing, inspection, and record keeping should depend on the size and complexity of the project.

It is further necessary that FRP systems be qualified in advance of a repair project. Due to the novelty and the proprietary nature of FRP repair technology, each manufacturer/supplier has its own FRP repair systems with subtle differences from those of others. Therefore, it is more appropriate to qualify a manufacturer/supplier for each of its FRP repair systems than to qualify "generic" FRP repair systems. This ensures not only the acceptability of the system, but also the competence of the manufacturer/supplier to provide it. The basic criteria for such qualification include related past experience and independent test data. In addition, the manufacturer/supplier must have a comprehensive training program to ensure that the contractor/applicator is appropriately trained to apply the system in the field. Similarly, the competency of the contractor/applicator must be demonstrated by providing similar related experience and evidence of training.

Some state DOTs require the manufacturer/supplier and the contractor/applicator to each issue appropriate warranties for the materials or the application of FRP repair system. Such warranties do not include routine maintenance of the FRP system. However, because warranties cannot be enforced, this issue was not included as part of the specifications.

Most state DOTs require methods of measurement and a basis of payment for all construction items. The proposed specifications include pay items related to substrate repair, corrosion inhibitors, wet lay-up systems, precured systems, near surface mounted FRP, and protective coating.

In order to produce an acceptable work, construction tolerances recommended by the manufacturer or set by the specifications or the contract documents must be followed. It is necessary to avoid accumulating tolerances in a job.

Fire is a life safety issue that needs to be considered while designing the FRP system. Most FRP systems are assumed to be lost completely in a fire because of their low temperature resistance. Fire resistance of FRP systems may be improved by adding fire retardants to the resin or by coating on the surface of the FRP.

3.2 ISSUES RELATED TO STORAGE AND HANDLING

Two important issues relate to the storage, handling, cleanup, and disposal of FRP repair systems: (1) preservation of properties and (2) safety issues. In order to preserve properties of fibers and resin, fibers and resin must be stored under appropriate temperatures and humidity conditions. Folding or bending may cause damage to fabric or precured strips. There are also time limits for storage of resin materials in unopened containers (i.e., shelf lives) and time limits for the use of mixed resin (i.e., pot lives). Because FRP-related projects deal with chemicals, safety of the personnel and the work place need to be considered diligently, and appropriate Occupational Safety and Health Administration (OSHA) rules must be followed, including appropriate training and knowledge of MSDSs.

3.3 ISSUES RELATED TO SUBSTRATE REPAIR

A clean and sound substrate is essential to the effectiveness of the FRP repair in achieving its intended design objectives. The issues for substrate repair include types of defects and methods of repair for the concrete substrate and the internal reinforcement. The work consists of several steps, including removal of defective concrete, repair of defective reinforcement, restoration of concrete cross section, and surface preparation.

Defects in concrete may include broken pieces, voids, spalling, and honeycomb. Damage may have resulted from deteriorations and corrosion or vehicle collisions (Figure 3.1). It is imperative that the damaged structure be properly prepared prior to the application of any FRP repair system. Improper treatment of concrete and the exposed reinforcement can lead to failure of the repair system. Any loose concrete remaining in the damaged region must be removed, leaving the member with sound concrete. Any corroded reinforcing steel must be repaired and treated (Figure 3.2). Improper waterproofing and splice details can allow further corrosion of the internal reinforcement, leading to loss of capacity and ductility. Damaged reinforcement may need to be spliced (Figure 3.3). 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 the corrosion process.

Restoration of a concrete section to its original shape may require small patching or considerable concreting with formwork (Figure 3.4). The quality and strength of the patching material and its bond with the existing concrete are important considerations. The bond may be enhanced with mechanical anchorage in the repaired region (Figure 3.5).

Surface preparation of the substrate is essential in achieving a good bond with the FRP repair system. The FRP repair applications are often categorized into two types: bond critical and contact critical (for example, see ACI 440 [*2002*]). Bond-critical applications refer to flexural or shear strength-

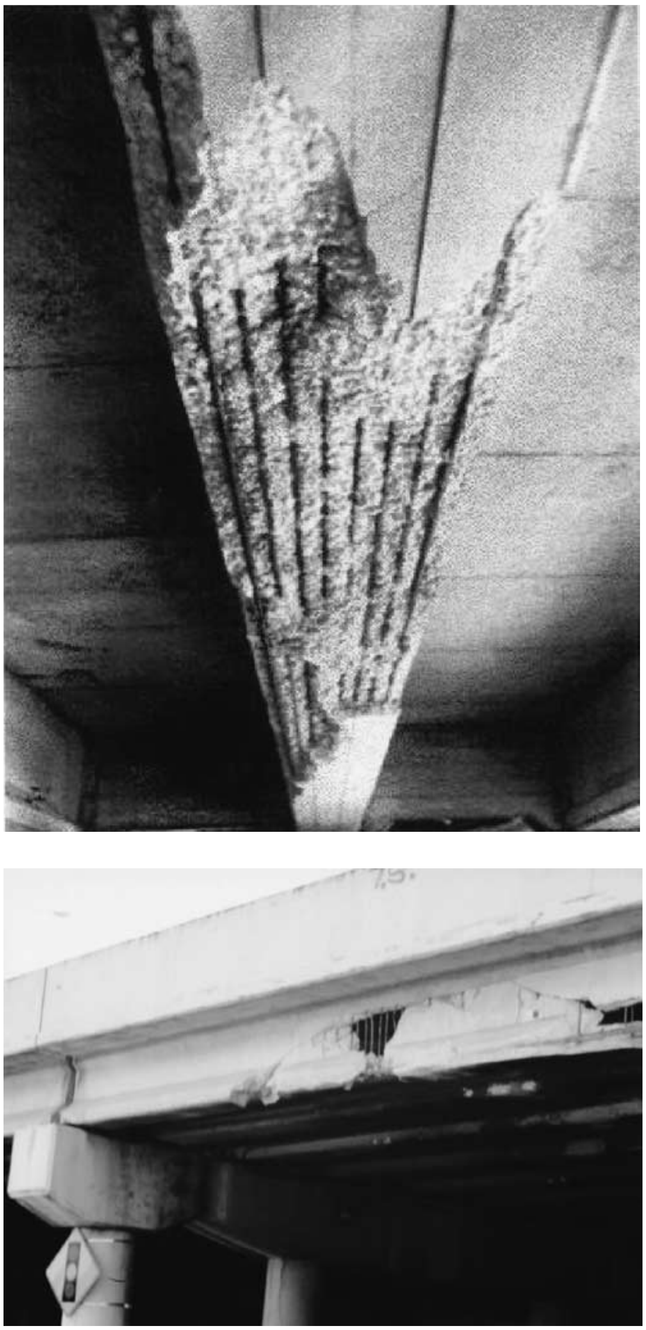

Figure 3.1. Examples of damages: corrosion (top) and vehicle collision (bottom).

Figure 3.2. Sandblasting of corroded steel.

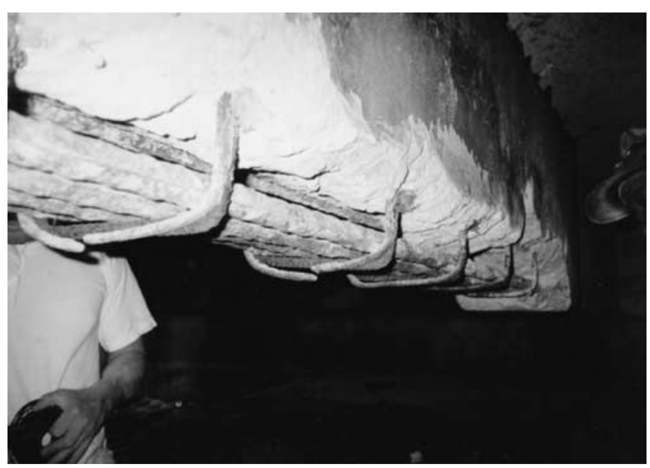

Figure 3.3. Splicing of damaged bars.

Figure 3.4. Forming concrete section.

ening of beams, slabs, columns, or walls, where bond between the FRP system and the concrete substrate is necessary for developing composite action and for transferring structural loads. Contact-critical applications refer to passive confinement of columns, where only intimate contact between the FRP system and the concrete substrate is sufficient to achieve the design objectives of containing concrete at the time of overloads. In developing these specifications, such distinctions were deliberately avoided for three reasons. Firstly, even though bonding may not be structurally necessary in the confinement of columns, it should be promoted for durability purposes. Many applications of column wrapping occur in aggressive environments. Any debonding between FRP and concrete that may result from less stringent criteria can lead to significant damage during freeze-thaw conditions. Secondly, adequate data are not available at this time to ensure that intimate contact provides passive confinement when necessary without allowing significant lateral dilation of concrete [*Mirmiran and Shahawy 1997, Shahawy et al. 2000*]. Thirdly, promoting bonding between FRP and concrete on all projects and for all surfaces can lead only to better construction practice at this early stage of development of the FRP technology [*Karbhari 1995*].

Surface preparation is concerned with several important issues: cleanliness; surface moisture, frost, and irregularities; cracks; and corners. The surface must be cleaned of all dusts by appropriate means (Figure 3.6). It must also be made free of moisture and frost before installing the FRP repair system. Surface irregularities affect the bond between FRP and concrete. They also may result in localized stress concentration. Such irregularities should be ground smooth within acceptable tolerances. As of yet, such tolerances are not based on sufficient test data, although research is underway at the University of Missouri-Rolla to determine the effect of surface profile on the performance of FRP repair systems. Cracks are known to cause delamination or fiber crushing. Tolerances for widths of cracks that must be filled are based primarily on the current practice and the practical limits of epoxy injection (Figure 3.7). Rounding the corners reduces stress concentration and results

Figure 3.6. Pressure washing of concrete.

Figure 3.5. Mechanical anchorage.

Figure 3.7. Epoxy injection of cracks.

in an improved bond between the FRP and the concrete surface. There are supporting data from the FHWA/University of Missouri-Rolla project on the effectiveness of FRP repair systems in sharp corners [*Yang et al. 2001a&b*] and on the selected tolerances for those applications.

3.4 ISSUES RELATED TO FRP REPAIR SYSTEMS

Three types of FRP repair systems were considered in this research: wet lay-ups, precured, and near surface mounted. Figures 3.8 through 3.11 show some examples of different applications. Near surface mounted FRP repair systems involve inserting and bonding FRP strips or rods into precut grooves. Some other FRP repair systems, such as automated or machine-applied installation of column wrapping, were not considered primarily because of rare usage.

Figure 3.8. Column wrapping.

Figure 3.9. Precured strips.

Figure 3.10. Precured shells.

FRP systems react differently to the environmental conditions and vary in mechanical properties. Issues related to the effects of environmental conditions on different FRP systems are shown in Table 3.1. The environmental conditions prior to and during the repair process are extremely important. They include ambient and surface temperature and moisture. Tolerances are set by current practice [*ICRI/ACI 1999*] for epoxy applications. Moisture restrictions do not apply to resins that have been formulated for wet applications.

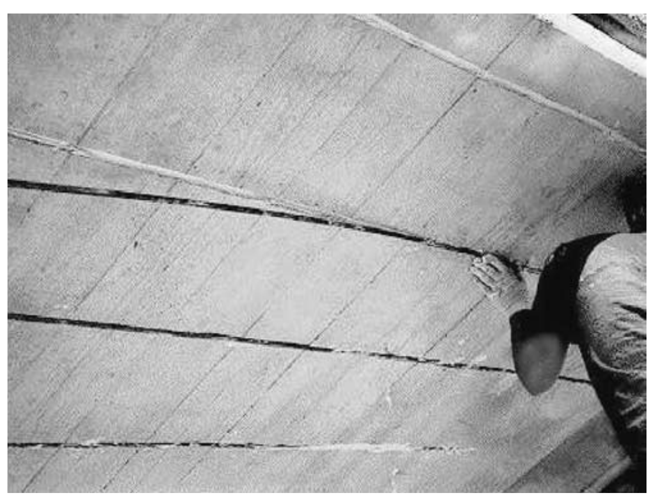

Figure 3.11. Near surface mounted rods.

TABLE 3.1 Environmental considerations for different FRP systems

Consideration	Carbon	Glass	Aramid
Alkalinity/acidity exposure	Highly resistant	Not tolerant	Not tolerant
Thermal expansion	Near zero, may cause high bond stress	Similar to concrete	Near zero, may cause high bond stress
Electrical conductivity	High	Excellent insulator	Excellent insulator
Impact tolerance	Low	High	High
Creep rupture and fatigue	High resistance	Low resistance	Low resistance

The primary issues for FRP installation include application of adhesives, FRP sheets or precured laminates, and protective coatings. Resins must be mixed at appropriate environmental conditions and must be used within their pot life. Application of the resin must be such that air voids are not present. Alignment of fiber sheets or precured laminates and any necessary overlaps in multiple layers also affect the performance of the FRP system. Tolerances for misalignment of fibers are set according to current practice and the expected behavior based on classical laminate theory. Other issues that need to be addressed for all systems are the anchoring of the FRP. Moreover, prestressing of FRP systems are covered.

Wet lay-up and precured FRP systems may be prestressed to improve their performance. Prestressing may be developed using active end anchorages in linear applications for beams or using pressure grouting in circular application for active confinement of columns. Early experiences with the active confinement of concrete columns in California have shown the susceptibility of glass FRP systems to creep rupture. Therefore, active confinement is not recommended for glass FRP systems. Moreover, the prestrain in carbon FRP systems should be limited to 50% of the ultimate strain due to damage tolerance concerns with unidirectional carbon FRP.

3.5 ISSUES RELATED TO INSPECTION

The main issues for the construction inspection include responsibility and criteria for the inspector, methods of inspection, record keeping, critical items requiring inspection, sampling frequency and location, and acceptance criteria. The inspector is considered to be the owner's representative, independent from the manufacturer/supplier and the contractor/applicator.

Critical items for inspection include received materials, substrate repair, surface preparation, fiber orientation, debonding, cure of resin, adhesion, and cured thickness. Records of daily inspections may include conditions of the environment (e.g., temperature, humidity, and rain); surface conditions; surface profile; width of cracks not injected with epoxy; batch numbers; mixture ratios; mixing times; qualitative descriptions of the appearance of all mixed resins, primers, putties, saturants, adhesives, and coatings; observations of progress of cure of resins; conformance with installation procedures; adhesion test results (i.e., 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 general progress of work. The owner shall be provided with the inspection records and samples.

Visual inspection, acoustic tap testing, laboratory testing of witness panels or resin-cup samples, direct pull-off testing, and core samples were selected as the most applicable methods of QC. In addition, nondestructive testing, auxiliary tests, and load tests may be used for specific projects. Sampling frequency and location as well as acceptance limits were chosen according to the current practice, as were the practical limits that may be placed on the project. These values, however, depend also on the project size and complexity. Therefore, more complex projects may require more advanced nondestructive tests.

Bridge inspectors are quite familiar with tap tests and simply need to be trained to hear the difference between bonded and unbonded laminates, which is somewhat similar to the difference between sounding concrete with and without delaminations. Infrared thermography may not be needed in most cases, but is an established technique for scanning large areas and identifying voids beneath the laminate.

Table 3.2 shows the available American Society for Testing and Materials (ASTM) standard test methods for FRP laminates used in repair and retrofit. It should be noted that the ACI Committee 440 is in the final process of approving "Guide Test Methods for Fiber Reinforced Polymer (FRP) Bars and Laminates," where new test methods are suggested for tensile properties of flat laminates, direct tension pull-off, and overlap splice tension. Clearly, as new test methods become available, the inspection procedures will need to be reevaluated.

3.6 ISSUES RELATED TO REPAIR OF DEFECTIVE WORK

Repair of all the defective work after the minimum cure time for the FRP should comply with material and procedural requirements defined in the construction specifications. Of importance are the type and size of defects, methods of repair, and acceptability of repair. Repair should restore the system to the designed level of quality and strength. The method of repair depends on the size and type of the defects. While small and localized defects can be easily injected with epoxy,

TABLE 3.2 Available test methods for laminates used in repair and retrofit

No.	Property	ASTM Test Method	Test Description
1	Tensile Strength and Modulus	D3039	Test Method for Tensile Properties of Polymer Matrix Composite Materials
2	Bond Strength	D4541	Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Tester
		C882	Standard Test Method for Bond Strength of Epoxy-Resin Systems Used with Concrete by Slant Shear
3	Inter-Laminar Shear Strength	D3165	Standard Test Method for Strength Properties of Adhesives in Shear by Tension Loading of Single-Lap-Joint Laminated Assemblies
		D3528	Standard Test Method for Strength Properties of Double Lap Shear Adhesive Joints by Tension Loading
4	Transition Temperature	D3418	Test Method for Transition Temperatures of Polymers by Differential Scanning Calorimetry

larger defects may require replacement of large portions of the repaired area.

3.7 ISSUES RELATED TO PROCESS CONTROL

The process control manual ensures that the specifications are properly and adequately followed and that the FRP repair project is performed in a manner that conforms to contractual and regulatory requirements. Determination of the conformance of the contractor's work to the requirements is verified on the basis of objective evidence of quality. The manual can be used by the owner or the designated field representative to ensure quality throughout the project. The manual describes how the QA program is designed to ensure that all quality and regulatory requirements are recognized and that a consistent and uniform control of these requirements is adequately established and maintained. The QC issues should cover the entire project, from the contract documents to the actual repair and postrepair work. The primary issues related to the process control manual include QA policy, QA responsibilities, elements of QA plan, QA procedures, record keeping, and implementation.

3.8 KNOWLEDGE GAPS

The research project was concerned with identifying provisions in the construction specifications and process control manual that would need further refinements. In the evaluation of existing information, and upon careful review of the sources for the selected tolerances and thresholds in the two documents, the following gaps in the state of the art were identified:

- **Environmental Conditions:** Environmental conditions during the application have probably the most significant effect on the overall performance of the FRP repair system. Yet, very little is documented as to the direct correlation between such conditions and the long-term performance of the system. The data on what conditions are acceptable in terms of temperature and humidity are not yet readily available. One of the important conditions is the moisture during the cure of the resin. Although the deleterious effects of moisture are known, it is not known within what limits of moisture the overall long-term properties of FRP are duly affected.
- **Surface Preparation Tolerances:** Tolerances for surface irregularities and crack widths are not yet based on sufficient scientific data. Research is needed to identify the critical values for these aspects of surface preparation.
- **Durability:** Because the factors for durability are at best guesses and because the HITEC program on strengthening [*HITEC 2001*] will provide more comprehensive data that will enable better assessment of durability factors, it is noted that long-term durability of FRP materials, while good, is still not completely defined. Hence, care must be taken in applying durability factors. The HITEC program on FRP Composite Systems for Concrete Structure Repair and Strengthening [*HITEC 2001*] is currently underway to assess the effect of various environments on FRP systems for strengthening.
- **Defects:** Significant research is needed to determine critical defects, their identification using rapid methods of NDE techniques, and the effect of such defects on the performance of FRP repair systems.

CHAPTER 4

CONCLUSIONS, SUGGESTED RESEARCH, AND RECOMMENDATIONS FOR IMPLEMENTATION

4.1 CONCLUSIONS

NCHRP Project 10-59 has resulted in the development of two separate stand-alone documents: *Construction Specifications and Commentary* and *Process Control Manual*. These two documents are written in a format suitable for possible adoption by the AASHTO Highway Subcommittee on Bridges and Structures [*AASHTO 1998*]. The proposed specifications and process control can provide uniformity among different states and different projects for the bonded repair and retrofit of concrete structures using FRP composites. The two documents are based on then-current scientific and engineering knowledge, research findings, construction practice, performance data, and other information related to FRP constituent materials and FRP systems. The information was gathered from a literature search, existing databases, a questionnaire survey, telephone interviews, and a clearinghouse website. A number of issues and parameters relevant to FRP repair were identified on the basis of the collected data and were used in developing the construction specifications and the process control manual.

The proposed specifications include eight main sections: General; Submittals; Storage, Handling, and Disposal; Substrate Repair and Surface Preparation; Installation of FRP System; Inspection and Quality Assurance; Repair of Defective Work; and Measurement and Payment. The specifications cover three different FRP repair systems: wet lay-up, precured, and near surface mounted. The proposed process control manual covers QC/QA prior to, during, and after completion of the repair project. The manual consists of planning, record keeping, inspection, and QC tests. The manual includes the following main sections: Quality Assurance (QA) Policy and Program Overview, QA Guidelines for Construction Activities, Responsibilities, Preparation of a Project-Specific QA Plan, and Implementing and Monitoring of the QA Program. The manual also consists of a number of QA checklists for the FRP repair projects.

Critical review of the FRP research to date indicates a general consensus on the most relevant issues and parameters that must be addressed in the construction specifications and process control manual. However, the primary concern throughout this project has been to develop the rational basis for the tolerances, criteria, and procedures that were specified in the two documents. The novelty of the FRP technology and its subtle differences from the traditional repair systems are reflected in the proposed specifications. Some of the proposed provisions may appear more restrictive than the current practice for traditional materials. Although the industry may find such restrictions counterproductive for further development of new FRP technology, the main objective has been to help protect state DOTs from low-quality applications with major defects. The decision on relaxing or replacing those restrictions ultimately lies with AASHTO and its member states. The states can use the proposed specifications and process control as model documents that need to be tailored to the states' specific needs as well as to the size and intent of the project of interest. At the same time, it should be understood that as the FRP technology matures, and as new research data become available, some of those restrictions may be removed or relaxed. In the next section, the provisions in the two documents that need further refinement are identified for future research.

4.2 SUGGESTED RESEARCH

During the course of the research project, a number of provisions in the proposed specifications and process control were identified that would need further refinements. The primary concern was to develop a scientific database for some of the tolerances, criteria, and procedures that were specified in the two documents. In this section, recommendations are made for a possible Phase II of this project to accomplish these refinements. The suggested research items are ranked in order of importance with respect to improving the construction practice:

- **Training:** Education and training should be an integral part of Phase II of this project. It is necessary to develop a training course or courses for state DOT employees similar to courses created to teach the new load and resistance factor design (LRFD) Bridge Design Specifications. The courses could also be offered and tailored to serve the needs of contractors, consultants, and bridge inspectors. Such courses should be prepared in a multimedia format and should consist of an introduction to the FRP repair systems and its components; procedures for storage, handling, and disposal; methods of substrate repair and surface preparation; procedures for FRP installation; methods of inspection and QC tests; repair of defective work; and process QC/QA checklists. Issues related to FRP material selection, design, and performance monitoring are deferred to additional courses.

- **Testing and Monitoring Program:** It is important that the proposed construction specifications and process control be implemented in field applications. This will ensure applicability of the various components of the proposed documents. In addition, field application will allow monitoring of the long-term effectiveness of the bonded FRP repair using the proposed documents. The field application may be tied together with FRP repair projects of a number of state DOTs using funds from the IBRC program. The wide-spread testing and monitoring in different states and climates will provide better means for evaluating the effectiveness of the proposed documents.
- **Criticality of Defects:** Although there is a general consensus on the characteristics of a sound FRP system and on the type and size of defects that are absolutely unacceptable, the thresholds for critical defects are not yet sufficiently researched. Significant research is needed to determine critical defects, their identification using rapid methods of NDE techniques, and the effect of such defects on the long-term performance of FRP repair systems.
- **Criticality of Environmental Conditions:** Environmental conditions during the application have probably the most significant effect on the overall performance of the FRP repair system. Yet, very little is documented as to the direct correlation between such conditions and the long-term performance of the system. Data are needed on what conditions are acceptable in terms of temperature and humidity. One of the important environmental conditions is the moisture present during the cure of the resin. Although the deleterious effects of moisture are known, it is not known within what limits of moisture the overall long-term properties of FRP are duly affected. Research is needed to identify the thresholds for the environmental conditions.
- **Thresholds for Surface Preparation:** Tolerances for surface irregularities and crack widths are not yet based on adequate scientific data. Surface preparation directly affects the quality of the bond between the substrate and FRP, which in turn affects the performance of the FRP system. Improper bonding may cause failure due to the FRP system detaching from the concrete substrate at the bond line. Research has indicated that concrete surface roughness is a key factor. Performance of the FRP system also depends on the state of cracks in the concrete substrate. Small cracks may be left untreated or may be pressure injected with epoxy. Larger cracks may be cut and then filled with epoxy. The thresholds separating the three approaches may depend on technical considerations (e.g., viscosity of the epoxy) as well as economical ones. Consideration of the type of crack (i.e., shear or flexural) is also critical. Research is needed to identify the thresholds for these aspects of surface preparation.
- **Long-Term Effects of Construction Anomalies:** It is unquestionable that the long-term performance of FRP repair systems is quite sensitive to the processes by which the material is stored, handled, installed, and cured, as well as to the conditions of the substrate, both concrete and the reinforcing steel. It is equally and widely accepted that currently there are no methods for quantifying the effect of the FRP application processes on the long-term performance of FRP repair systems. Although some “accelerated aging tests” have been proposed and carried out [*Zureick 1998*], results from such tests have yet to be correlated with the field performance to accurately predict service life. Therefore, these tests can provide insight only as to the importance of parameters and issues, rather than actual tolerances, criteria, and procedures. The numerous existing field applications are relatively new and have yet to produce long-term performance data. Research is needed to correlate the accelerated aging tests with the actual field performance data so that necessary reduction factors can be developed for construction anomalies to account for long-term degradations.
- **Criticality of Bond for Confinement:** There is a question as to the necessity of bonding and intimate contact for confinement applications. For FRP systems to engage, concrete must crack and dilate. Therefore, it may not be necessary to provide the bond. However, further research is needed to address this issue.
- **Inspection and Maintenance:** Although the scope of this research was limited to construction of bonded FRP repair systems, regular inspection and maintenance of the repaired systems are equally important. Bridge inspectors are quite familiar with traditional materials, but are not well equipped to inspect and maintain a bridge that is repaired with FRP systems. No inspection guidelines exist to date. In the case of bonded FRP laminates, inspections should focus on the condition of the bond. It is necessary to develop recommended field procedures, evaluation guidelines, and reporting standards for periodic inspection of in-service FRP systems. There is a need for field inspection devices and standard test methods for inspection of FRP repair and strengthening work. Inspection procedures and test methods are essential tools that enable state DOTs, practicing engineers, and contractors to evaluate current practices in application of FRP and to exercise jobsite control of the quality. This ability is especially important for field inspection of bonded FRP repairs of concrete structures because the

performance of the system depends primarily on bond properties. The thresholds for each test method should be identified. Test methods should be rapid and economical techniques that can detect damage approaching or exceeding these thresholds. The three areas that need the development of inspection devices are surface roughness, bond strength, and voids/delaminations.

4.3 RECOMMENDATIONS FOR IMPLEMENTATION

Successful implementation of the proposed specifications and the process control manual requires a detailed program with the following four elements:

- **Training and Technology Transfer:** In order to adequately implement the proposed specifications and process control manual, bridge maintenance engineers, contractors/applicators, and manufacturers/suppliers must be fully conversant in and proficient with the new provisions. Technology transfer can be achieved through development and offering of comprehensive training courses on the use of the new provisions. These courses can be developed and offered through collaboration of the authors with FHWA, the AASHTO T-21 Committee, and the state DOTs. Initially, it is suggested that a 2-day training course be developed to cover the proposed specifications and the process control manual, as well as a multimedia introduction to FRP repair systems. The workshops may be offered at the TRB annual meetings in Washington, D.C. They may also be offered regionally with the participation of state DOTs. The workshops may be arranged through the National Highway Institute (NHI), which is a training arm of FHWA. The NHI currently offers a number of training courses, including "Bridge Inspection Refresher Training," "Engineering Concepts for Bridge Inspectors," "Bridge Coatings Inspection," and "Safety Inspection of In-Service Bridges."
- **Shakedown Period:** It is suggested that the proposed specifications and process control manual be adopted by AASHTO as a guide specification for an interim "shakedown" period. During this period, the maintenance engineers of the state DOTs, the composites industry, and contractors get a chance to closely examine the various aspects of the two documents and provide their input to the AASHTO T-21 Committee for further improvements.
- **Trial Field Applications:** It is also suggested that during this transition or "shakedown" period, the proposed specifications be tested and used in a series of trial field applications. Field applications of the proposed documents help identify areas for which provisions or guidance is unclear, inadequate, too loose, or too restrictive. Trial field applications therefore would provide an opportunity to improve the specifications before they become mandatory. It would be ideal if the trial field applications of the proposed specifications became integral components of the IBRC program for FRP repair projects. These applications help the state DOTs gain confidence in the proposed specifications and in their ability to implement them. Therefore, it is important that the field applications be diverse geographically, as well as diverse in the type of FRP system and size and scope of the project. Although the trial applications would be carried out by each individual state DOT separately from the testing and monitoring program that was outlined in the previous section, it would be extremely useful if the participating states adopt the same testing and monitoring program.
- **Updating Process:** Although every effort has been made to develop comprehensive specifications and process control, both documents need to be frequently updated and revised to keep up with the ever changing nature of FRP technology. The dynamic nature of the two documents will allow for future modifications as more research results become available. The burden of updating the documents lies with the AASHTO T-21 Committee.

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SECTION II:

RECOMMENDED CONSTRUCTION SPECIFICATIONS

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.

COMMENTARY

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.

SPECIFICATIONS

COMMENTARY

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.

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, nonwoven, 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.

SPECIFICATIONS

COMMENTARY

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.”

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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.

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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.

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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.

Volatiles—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.
- 117-90: Specifications for Tolerances for Concrete Construction and Materials, and Commentary.
- 224.1R-93: Causes, Evaluation, and Repair of Cracks in Concrete Structures.
- 224R-01: Control of Cracking in Concrete Structures.

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C1.3 Recommended References

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- 440R-96: State-of-the-Art Report on Fiber Reinforced Plastic Reinforcement for Concrete Structures.
- 440.2R-02: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening of Concrete Structures.
- 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*

- D3039: Test Method for Tensile Properties of Polymer Matrix Composite Materials.
- D3418: Test Method for Transition Temperatures of Polymers by Differential Scanning Calorimetry.
- D4541: Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Tester.
- D5687: Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation.

ICBO—*International Conference of Building Officials*

- AC125: Acceptance Criteria for Concrete and Reinforced and Unreinforced Masonry Strengthening Using Fiber-Reinforced Polymer (FRP) Composite Systems.
- AC178: Acceptance Criteria for Inspection and Verification of Concrete and Reinforced and Unreinforced Masonry Strengthening Using Fiber-Reinforced Polymer (FRP) Composite Systems.

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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.

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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.

C2 SUBMITTALS

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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 prequalified by the owner or its representative for each of its FRP systems after providing the following necessary information:

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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-

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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 prequalified 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.

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resentative 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.

3 STORAGE, HANDLING AND DISPOSAL

3.1 Storage

3.1.1 Storage Requirements

All components of the FRP system must 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

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

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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

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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,

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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 (1/2 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 (3/4 in.) or at least 6.4 mm (1/4 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

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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-

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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.

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rosion process [*Harichandran and Baiyasi 2000, Sohanghpurwala and Scannell 1994*]. Precautions may be necessary in cases of carbonation, alkali-silica reactivity (ASR), or reactive aggregate.

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 $\times$ 102 mm (4 in. $\times$ 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

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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 grinded 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

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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 Surface Preparation

Surface roughness has a significant effect on the bond between the FRP system and concrete [*Shen et al. 2002*]. Surface preparation depends on the type of application and the type of FRP system. Even though bond may not be structurally necessary for contact-critical applications such as confinement of columns, it would help improve durability of the structure. Many applications of column wrapping occur in aggressive environments. Any debonding between FRP and concrete that may result from less stringent criteria could lead to significant damage during freeze-thaw cycles.

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.

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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.

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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.

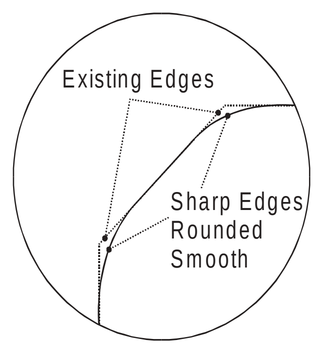

Figure C4.4.2. Chamfering Corners

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.

C4.4.3 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.

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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.

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.

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.

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.

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.

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.

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-

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

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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

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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

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contract documents, or required by the engineer for safety. Shoring shall not be removed until the FRP system has fully cured and gained its design strength, as recommended by the manufacturer and approved by the engineer.

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

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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.

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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.

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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/m^2 (0.1 lb/ft^2).

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.

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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

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C5.4.5 Multiple-Fiber Plies

Some repair and retrofit applications may require more than a single-fiber ply to be installed by wet lay-up. The waiting time between plies depends on the type of resin, the type of fiber sheet, and the ambient temperature. It is good practice to wait for the resin to fully impregnate the fibers to avoid forming air pockets. The rate of coverage of the resin overcoat is listed on the system data sheet, but generally depends on the type of resin and fibers and the ambient temperature. The typical rate of application is about 2.4 kg/m^2 (0.05 lb/ft^2). Application of too many plies in a single day may result in slippage or separation because of the self-weight of fiber sheets. The number of plies that can be applied in a single day depends on the ambient temperature, the weight of the fiber sheet, and whether the repair is overhead or on a vertical surface.

C5.4.6 Overlapping

When the length of the sheet to be installed exceeds the length suggested by the manufacturer for proper installation, lap jointing becomes necessary. Lap splice length depends on the type of resin and fibers [*Yang and Nanni 2002, Belarbi et al. 2002*]. For large coverage areas, it is recommended that all lap joints in the longitudinal direction of fibers be made in a single day. Transverse lap joints, if necessary, may be made in several days.

C5.4.7 Alignment of FRP Materials

Performance of a unidirectional FRP system depends heavily on fiber orientation and straightness. Misalignment may occur because of improper rolling or wrong placement of fiber sheets. Fiber misalignment is known to affect the strength more significantly than the elastic modulus [*Yang et al. 2002*].

C5.4.8 Anchoring of FRP Sheets

Anchoring of fiber sheets helps prevent delamination failure of the FRP system. Different methods can be employed to anchor the fiber sheets. When possible, U-wraps may provide additional

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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.

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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/m^2 (0.1 lb/ft^2). 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.

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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

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C5.5.3 Anchoring of Precured System

Temporary clamping and shoring may be necessary in overhead applications of the precured systems until the adhesive cures.

C5.5.4 Grouting of Precured Shells

Pressure grouting creates an active confinement in the column. Active confinement with glass FRP systems is NOT recommended because of concerns related to creep rupture. The prestrain in carbon should be limited to 50% of its ultimate strain, as described in Section C5.4.9.

C5.5.5 Stressing Applications

Prestressed FRP systems often require proprietary materials, procedures, and anchoring systems. The stressing hardware may be found on the shop drawings, as specified in Section C2.1. The movable anchorage generally cures in 24 hours, while the fixed anchorage takes about 48 hours to cure. Prestressing of glass FRP systems is NOT recommended because of concerns related to creep rupture. Prestressing of carbon FRP systems above 50% of the ultimate strain may affect damage tolerance, hence requiring additional protection against accidental impact.

C5.6 Application of Near Surface Mounted FRP Systems

The NSM FRP system allows for anchoring the reinforcement into adjacent members and upgrading members in their negative moment

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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.

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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.

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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 1⁄64 in.) and No. 6 (3.36 mm or 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

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C5.8 Protective Coating and Finishing

Protective coating is applied for aesthetic appeal or protection against impact, fire, ultraviolet and chemical exposure, moisture, or vandalism. FRP systems are usually durable to weather conditions, sea water, and many acids and chemicals. Mortar finish can provide protection against impact or fire. Weather-resistant paint of the family of urethane or fluorine or epoxide can provide protection against direct sunlight. The proper amount of paint finish coat is usually indicated in the shop drawings, as specified in Section C2.1. Use of solvent wipes may cause deleterious effects on polymer resins. Abrasive cleaning is generally not required when the first coat of paint is applied within 2 or 3 days after mixing the components for the final 15-mil resin coating. It is a good practice to allow a minimum of 1 or 2 hours before applying the second coat. The engineer may request that the contractor provide a sample mock-up of the coating system for about a 0.1-m^2 (1-ft^2) area.

C5.9 Temporary Protection

Temporary tents or a plastic screen may help protect the installed FRP system against rain, dust, dirt, excessive sunlight, extreme temperatures, and high humidity. The temporary protection may also serve as a deterrence for vandalism.

C6 INSPECTION AND QA

The specific QA plan for each project may be developed from the tests identified in this section according to the size and complexity of the project. Checklists for QA are provided in the accompanying process control manual.

C6.1 Inspection of Materials

Testing in this section is for acceptance and not for qualification. For qualification testing, consult with the AASHTO Materials Specifications for FRP Systems when it becomes available. The

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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 m^2 (1 ft^2). Defects smaller

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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 (1/4 in.) in diameter will require no corrective action, unless as specified in Section 7.2. Defects larger than 6.4 mm (1/4 in.) but smaller than 32 mm (1 1/4 in.) in diameter will be repaired as per Section 7.2. Defects larger than 32 mm (1 1/4 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.

et al. 1996], microwave detection [*Hughes et al. 2001*], or infrared thermography [*Mandic et al. 1998*] may be performed, if specified in the contract documents or approved by the engineer, when an area is deemed to be suspect.

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.

C6.5 Inspection for Cure of Resin

Data on resin cure time and temperature are specified on system data sheets. The sampling frequency depends on the size and complexity of the project. For visual inspection of the cure of resin, the inspector may use physical observation of resin tackiness and hardness of work surfaces or hardness of resin-cup samples.

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 m^2 (1,000 ft^2) 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.

C6.6 Inspection for Adhesion

The sampling frequency depends on the size and complexity of the project. It is recommended that test locations be on flat surfaces and representative of the variations in the FRP system and the concrete substrate. If possible, test areas need to be selected where lower stresses are expected during service conditions. Other adhesion tests such as a surface adherence shear test or a torque test may be used if specified in the contract documents or approved by the engineer. It is recommended that an initial pull-off test be conducted on 0.1-m^2 (1-ft^2) sample coverage of the FRP system on the concrete substrate before the installation proceeds. This will ensure that the FRP system will work effectively.

6.7 Inspection for Cured Thickness

If specified in the contract documents or required by the engineer, 12.7-mm (1/2-in.) diame-

C6.7 Inspection for Cured Thickness

The sampling frequency depends on the size and complexity of the project. Instead of tak-

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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.

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ing additional cores, the same samples from the adhesion tests may be used for measurement of the cured thickness. If possible, core samples should not be taken from high-stress or lap splice areas.

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*].

SPECIFICATIONS

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 m^2 (10 ft^2). Small defects of size between 6.4 and 32 mm (1/4 and 1 1/4 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

COMMENTARY

C7.1 Repair of Protective Coating

Although primarily aesthetic in nature over the short term, defects in protective coating may cause long-term degradation of the FRP system because of concentrated moisture ingress. Local defects in coatings are analogous to cracks or blistering in the epoxy coating of steel bars. Surface cracks may develop for a variety of reasons. They are often nonstructural and may be due to excessive coating thickness, excessive shrinkage during cure, or external abrasion. Sandblasting and rotary water pressure should not be used to remove the coating because they leave small pits and craters that cause damage to the FRP system. Blisters are caused when moisture passes through the outermost layer and then causes the development of osmotic pressure from within. Blister is often a sign of moisture entrapment, and hence all moisture needs to be removed prior to applying another coat to ensure that further damage is not caused after recoating. Large localized blisters are often a result of solvent softening of the coating. Spot repairs should be conducted with a two-part epoxy only. Signs of excessive peeling indicate that the original coating was applied incorrectly and are most often due to inappropriate surface preparation of the FRP system. Applying a new coating directly on top of the old peeling or any defective coating encapsulates the defects and accelerates internal degradation, which in turn causes rapid deterioration of the new coating itself.

C7.2 Epoxy Injection of Small Defects

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 (1¼ 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 cleaned 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.

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.

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.

C7.4 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.

obtain approval from the engineer before extending the limits of concrete removal from those clearly identified in the contract documents. Crack injections may also be measured as the number of locations, crew days, or lump sum.

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.

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SECTION III:

PROCESS CONTROL MANUAL

The primary objective of the process control manual is to ensure that bonded repair and retrofit of concrete structures using FRP composites are conducted in a manner that conforms to contractual and regulatory requirements. Conformance of the contractor's work to the requirements is verified on the basis of objective evidence of quality. This document supplements the construction specifications for bonded repair and retrofit of concrete structures using FRP composites.

The process control procedures and the systems outlined herein describe how the quality assurance (QA) program is designed to ensure that all quality and regulatory requirements are recognized and that a consistent and uniform control of these requirements is adequately established and maintained.

The success of the QA program depends on (a) thorough understanding of its aims and (b) its full implementation by the owner's representatives.

1 QA POLICY AND PROGRAM OVERVIEW

1.1 QA Policy

The QA program has been developed to ensure that the project is carried out in a planned, controlled, and correct manner. It includes procedures for scheduling and assigning work; recording, retaining and retrieving records for all construction activities; identifying and resolving deficiencies affecting the work; and verifying compliance with the requirements of the QA program.

The QA program can be modified, if necessary, to meet the needs of individual projects or to comply with any specific requirements or agreements. The program will implement those requirements and agreements by applying them to specific activities and will identify the items and services to which the program applies.

The QA procedures (QAPs) define the organizational structure within which the program is to be implemented and delineate the responsibility and authority of the various personnel involved.

The QA program will be periodically reviewed, audited and updated for improvement, as necessary.

1.2 QA—An Overview

1.2.1 Quality Definitions

- Quality Assurance (QA)—Established philosophy, programs and organization covering activities whose purpose is to ensure that the overall quality control program is being effectively implemented.
- Quality Control (QC)—A planned system of activities whose purpose is to provide a level of quality that meets the needs of users.

1.2.2 QA/QC Goals

- Develop staff understanding and acceptance of QA philosophy and procedures.
- Develop staff understanding of their particular roles in implementing QA/QC procedures.
- Meet the owner's need for a quality product.
- Ensure that appropriate procedures are followed at each step of the process from the inspection of incoming raw materials to the application of the final coating to achieve a specified performance.

1.2.3 Elements of QA Program

- Set out QA philosophy and QC procedures.
- Establish corporate and office QA staff functions.
- Host seminars on QA philosophy and QC procedures and other aspects relating to high-quality services and deliverables.
- Implement QA/QC procedures.
- Monitor adherence to policy and procedures.
- Monitor schedule adherence and check deliverables at milestones.
- Identify the type of contract to be signed and check for unrealistic responsibilities, warranties, indemnifications and ambiguous wording.

2 QA GUIDELINES FOR CONSTRUCTION ACTIVITIES

2.1 Responsibilities

2.1.1 QA Manager

The QA manager is responsible for the development and the implementation of the QA program and for ensuring adherence thereto. The QA manager monitors and audits all project activities on a systematic basis, documents the findings in project audits, and reports the findings to the unit manager, the project manager, or technical department managers, as appropriate. The QA manager also identifies the corrective measures for all noncompliances with the QA program. The QA manager has the overall authority of initiating, redirecting or terminating activities so that they are consistent with the QA program. The QA manager may (a) initiate any activities that will ensure adherence to the QA program and (b) utilize the personnel necessary to properly administer the QA program. Specific duties of the QA manager include the following:

1. Developing, modifying, updating and implementing the QA program.
2. Assisting the unit managers in implementing the provisions of the QA program.
3. Assisting the project manager in establishing project-specific QA requirements based on the owner's special needs and the established standard procedures.
4. Instructing project personnel in using the QA procedures.
5. Monitoring adherence to the QA program.
6. Approving QA programs of contractors, subcontractors, and consultants, where required.
7. Providing input for reports, specifications, and other documents, where QA information is required.

2.1.2 Project Officer

The project officer is responsible for the preparation of letters of interest and proposals and for assisting in negotiations and finalizing the contract. Specific duties of the project officer during different phases include the following:

1. During the proposal phase:
   a. Developing the project scope in conjunction with the owner's goals and objectives.
   b. Determining QA program requirements and special QA procedures to be followed in the work process.
   c. Establishing the proposed project budget, schedule and staffing requirements.
   d. Directing the preparation of letters of interest, proposals and contracts.
   e. Participating in the negotiations.
   f. Signing the letters of interest, proposals and contracts.
2. During the selection phase:
   a. Selecting final prospective contractors, subcontractors and consultants.
   b. Establishing the work scope, schedules and budgets.
   c. Assisting in contract negotiation.
   d. Drafting and finalizing the contract terms.
   e. Disseminating all proposal and contract information to the project manager and other appropriate staff members.
   f. Establishing proposal budgets and schedules and controlling the costs during the precontract stage.
3. During the implementation phase of the project:
   a. Monitoring the project performance and the financial status.
   b. Meeting with the project parties, as needed, to assess work progress and address any possible concerns.

2.1.3 Project Manager

The project manager is responsible for maintaining liaison with different parties, as well as overall responsibility for all technical and administrative aspects of the project. The project manager reports to the project officer and the unit manager, as required. The project manager has the authority to make modifications to the requirements of the QA program in order to comply with the owner's special requirements and to suit objectives of a particular job. The project manager will also determine which QA procedures are to be followed and will modify those procedures as necessary to suit specific job requirements, all subject to the approval of the QA manager. Specific duties of the project manager include the following:

1. Review the project scope, contract plans and specifications for construction-related services.
2. Satisfy the organizational needs, equipment and staffing requirements to adequately implement required QA program activities.
3. Implement and monitor the QA program activities for the project.
4. Monitor compliance with the provisions of the contract.
5. Maintain the relation between the owner and the contractor.
6. Resolve errors and omissions on construction plans and specifications and assist in the solution of technical problems.
7. Receive all project information and properly disseminate it to the appropriate staff members.
8. Approve reports, specifications and drawings.

2.1.4 Resident Engineer

Responsibilities of the resident engineer include the following:

1. Review construction plans and specifications and review the contract for construction-related services.
2. Establish QA program activities, responsibilities, and documentation requirements.
3. Implement and administer the day-to-day QA program activities to verify conformance to the plans, specifications and the referenced quality standards. Expedite distribution of the QA program documents and information.
4. Coordinate QA program activities with the project manager, the design engineer, the contractor and its

subcontractors. Receive and review staff comments on the quality of the work and take action as required. Advise the project manager of potential or existing quality problems.

5. Review and evaluate all required inspections, nonconformances and audit reports. Ensure that reports are timely, accurate, distributed and reconciled. Address and resolve quality problems reported by the construction inspectors. Verify that the contractor's QC procedures and reporting systems are adequately established, accurate and current.
6. Assist the project manager in evaluating the staffing requirements and qualifications of project personnel. Verify individual qualifications.
7. Review technical information submitted by the contractor to ensure conformance to the submittal requirements of the plans and specifications.
8. Direct all required inspections of the procured materials for incorporation in the project work. Monitor the quality certifications, proper quantities, and required identifications. Monitor inspection for, and documentation of, any shipping and/or storage damages.
9. Review test reports of the materials to verify that the specified tests have been performed in the required number or frequency. Indicate conformance or nonconformance with the plans and specifications and referenced quality standards.
10. Instruct and train the construction inspectors in their particular duties pertaining to the current and upcoming project work.
11. Review and evaluate claims, requests for change orders and time extensions in accordance with the provisions of the plans and specifications. Make recommendations to the project manager for resolution of any contractual dispute.
12. Supervise all administrative services needed to document the construction process.
13. Report work progress, schedule, tests and contractual matters, as specified.

2.1.5 Office Engineer

Responsibilities of the office engineer include the following:

1. Develop and maintain the QA program records system and the project-filing index in cooperation with the resident engineer. Monitor the activities of recording clerks.
2. Receive, file and distribute to designated recipients the QA program all documents produced by the construction inspectors, the resident engineer, testing laboratories and the contractor.
3. Monitor and evaluate, under the direction of the resident engineer, the reporting of quality data.
4. Assist the resident engineer in monitoring the contractor's QC programs. Verify implementation of the contractor's QC documentation at all levels of inspection.
5. Verify the quality documentation of furnished materials and equipment upon arrival at the construction site.
6. Review material test reports for adequacy, completeness, and conformance to specifications and the referenced quality standards.
7. Provide accurate reporting of all QA program activities to verify compliance with the plans and specifications. Assist construction inspectors with the production of QA program records.
8. Produce, or secure and maintain for use, a set of up-to-date "as-built" or record drawings. Verify accuracy, current revisions, and reproducibility of "design" drawings and their certification. Verify the distribution of up-to-date contract documents to the field staff and the contractor.
9. Verify that materials incorporated in the work are identified by dates, bulletin numbers, change order numbers, signatures and other pertinent data requirements.
10. Act, in the absence of the resident engineer, on matters concerning the QA program for the project.
11. Maintain the QA program files to provide identifiable, retrievable and reproducible construction documents; include contract drawings, specifications and records of incorporated materials and equipment, tests and inspection data.

2.1.6 Construction Inspectors

Responsibilities of the construction inspectors include the following:

1. Maintain daily contact with the resident engineer and the office engineer, and assist in the implementation of the QA program activities.
2. Perform daily visual on-site inspections of construction quality and materials. Document project activities, payment quantities and QA program activities. Prepare daily inspector's reports (DIRs). Coordinate inspection activities with the inspections of the contractor, the materials test laboratory technicians, and the owner's representatives according to the scheduled QA program activities.
3. Witness all required field tests by the contractor. Verify that the individual performing the test signs the test documentation. Indicate witnessing the test where applicable, date the document, and indicate concurrence with the results.
4. Verify during preparatory inspection meetings with the contractor representatives that contract-required engineering and quality-related documents have been submitted and approved prior to commencing the work.

5. Advise the resident engineer of potential or existing quality problems.
6. Record tests witnessed and inspections performed on the DIR, and verify that the report is timely, accurate and signed.
7. Review material test reports to verify that the specified tests are performed in adequate number and that the results are in accordance with the contract plans, specifications, and the referenced quality standards.
8. Assist during receiving inspections of materials and equipment for proper quantity, identification of any shipping damage, and conformance with the procurement documents. Receive and file certificates of compliance, shipping documents and logs.
9. Maintain testing equipment in working order. Arrange for calibration of test equipment at required intervals. Document calibration of test equipment.
10. Verify that work in the field is performed in accordance with contract plans and specifications. Ensure that plan sets issued for construction are current.
11. Coordinate with or assist survey crews to verify correct locations, alignments and elevations of ongoing or completed work.

2.2 Preparation of a Project-Specific QA Plan

2.2.1 Project Start-Up Considerations

An important QA element before starting a construction project is becoming fully familiar with the intent and details of the plans and specifications. Identifying any apparent errors, omissions or ambiguities early in the project will help ensure quality and will limit change orders and contractual disputes. The project start-up duties for the project team include the following:

1. Review the contract for the performance of construction-related services and list those administrative, inspections, observation duties and procedures for which the contractor is responsible. A sample of duties that the contractor is solely responsible for includes the following:
   a. Contractor's means and methods for construction.
   b. Safety of contractor's work force.
   c. Contractor's adherence to schedule, etc.
2. Assisted by the chief or senior construction inspector, review the construction contract documents (plans and specifications) between the owner and the contractor. List all administrative, procedural, inspection, and field testing responsibilities to be performed. At this stage, any discrepancies and ambiguities in the duties and responsibilities should be identified and resolved prior to proceeding with the project.
3. Understand the impact of any imposed environmental, phasing or operational limitations or constraints on the construction processes.
4. Review the proposed project staff and organization for the following:
   a. Adequacy of staff positions needed to cover the contractual obligations.
   b. Required staff licensing and certification.
   c. Technical qualifications and experience of assigned personnel, contractors and its subcontractors for specialty services.
   d. Need for staff training in specific inspection procedures, safety awareness, and limitations in the authority, relations with the contractor, its subcontractors, the owner, and the public.
5. Review the physical aspects of the project work area and adequacy of the facilities provided to house construction site staff.
6. Verify the availability of measuring and testing (M&T) equipment and instruments needed to verify the quality of components to be incorporated into the finished work. Check that licenses needed to own, store, or operate M&T equipment are on file. Determine which testing will be done in-house and which will be done by an independent facility.
7. Ensure availability of all forms needed to document the quality of the constructed project and its administrative processes.

2.2.2 Considerations Related to the Verification of Quality of the Constructed Project

Review the contract agreement for the specific obligations related to the following.

2.2.2.1 Document Control

Establish procedures for issuance and transmission of design revisions and addenda to the plans and specifications, shop drawings, staging and phasing plans, traffic control plans, contractor's required submissions of work plans, schedules and general correspondence.

2.2.2.2 Constructability Review

Following are important items to consider during the constructability review:

1. Check for realistic scheduling of work activities. Identify need for overtime and double-shift work and unusually high-peak demand for machinery and construction plant.
2. Check the proposed construction schedule for compatibility with sequencing and phasing of the work, as related to natural phenomena, such as high flood periods, hurricane seasons, high tides and general inclement weather periods.
3. Check for proper sequencing of operations. Identify any operations that are on the critical path and that

could cause delays and possible loss of a construction season.

4. Check for adequate rights-of-way and access to the construction areas. Verify adequacy of areas reserved for contractor's work, lay down and storage areas.
5. Check for interference with traffic, utilities and other ongoing or sequential contract work by others.
6. Identify long-lead items and the need for unusual construction materials and equipment.
7. Check for use of appropriate materials and up-to-date designs and technology. Identify the use of unconventional or highly specialized designs or expensive materials, which could limit competition and result in high bids. Verify that new materials are being used in the manner intended by the manufacturer.
8. Check contract documents for ambiguities and inconsistencies that could lead to schedule delays, contractual disputes and possible legal actions. Verify that details shown are adequate to ensure proper erection and construction sequencing.
9. Check for community impacts such as noise, dust, and release of toxic or otherwise unsafe materials into the environment.
10. Check for conformance to all governmental regulations that safeguard the environment, the work place and the public.
11. Check that accessibility for maintenance, repair and in-service inspection has been provided. Review maintenance, repair and inspection requirements and verify that the design shown on the drawing provides adequate access for these activities.
12. Avoid duplication of data in the specifications and the drawings by ensuring the following:
    a. Dimensions are correct and consistent, and tolerances are appropriate.
    b. Drafting practices conform to the standards specified.
    c. Drawings are legible.
    d. Drawings reproduce satisfactorily.

2.2.2.3 Quality Aspects of Construction Specifications

Problems related to the specifications that may lead to change orders, claims, arbitration and litigation are broken down into the following categories in descending order of frequency.

"Or Equal" Specifications

To avoid problems with "or equal" specifications, it is best to list those physical or functional properties of the name brand product you wish to see duplicated in the "or equal" product.

Constructability

Contract documents may be defective if the work shown is not reasonably constructible. Remember the ordinary sequence of trades in the construction process, and look for bad phasing or details that require a succeeding trade to install something before the preceding trade would normally arrive on the job.

In setting the tolerances, be sure that they follow industry standards or are no more stringent than contained in standard specifications. If more stringent tolerances are required, word the specifications so that the contractor's attention is alerted to this fact so that he/she can adjust his/her normal work methods and pricing to achieve the results required.

Overly strict or literal interpretation of the specifications on tolerances beyond the normal industry standards generally results in change order decisions in favor of the contractor.

Ambiguities and Typographical Errors

Ambiguities in the specifications are usually the result of duplication, which is to be avoided. If there are two ways of reasonably interpreting documents, the courts will usually side against the preparer. The use of standard specifications will help reduce this category of problems.

Conflicts Between Plans and Specifications

Specifications usually contain a clause in the general provisions establishing an order of precedence between the various contract document components:

1. Signed contract
2. Other provisions such as special conditions
3. General provisions
4. Plans
5. Technical specifications

To minimize conflicts between plans and specifications, it is important to avoid duplication. Avoid repeating the same information in plans and specifications. If an entire specifications section is in the plans, that section should be omitted entirely from the specifications. Construction contracts frequently contain a clause that in effect says that anything mentioned in the specifications and not shown on the plans or shown on the plans and not mentioned in the specifications shall be interpreted as being shown or mentioned in both. The case of an item mentioned only in the specifications and not shown on the plans can lead to change orders on the basis that the contractor had adequate information as to quality, but was unable to assess the cost of installing the item because its physical relation to other project components was not defined or was lacking. Leaving something out of the specifications that is shown on the plans leaves open the possibility for the contractor to supply the cheapest possible alternative.

Inspection Requirements

Overly restrictive tolerances have been discussed above. Inspection or observation of the contractors' work invariably creates some interference with the performance of the work by the contractor. Frequency of tests and observations should be in line with the normal industry standards or the standard specifications. Failure to adhere to the industry norms may produce claims. Overzealous or inconsistent inspection, although not part of this general subject, also is a frequent cause for change order claims in this category.

Safety and Health Requirements

Failure to comply with local codes can result in lawsuits, charge-backs, or awards against the design engineer.

2.2.2.4 Product Identification, Traceability and Certification

1. Establish procedures for identifying materials and products, including documentation needed to verify the quality of products and materials, such as batch plant records, laboratory tests, catalog cuts and any other documentation.
2. Comply with storage requirements to prevent deterioration of materials and products at the work site, including preventive maintenance while in storage.
3. Comply with requirements for identification, rejection, or segregation of substandard or unacceptable materials or products.
4. Comply with requirements for identification of certified materials and identification of the status of tests and inspections for incorporated materials, including specified marking, tagging, and stamping and/or physical isolation.

2.2.2.5 Process Control

Comply with requirements in regard to specified construction processes.

2.2.2.6 Inspection and Testing

The contract plans and specifications should be checked for any testing requirements, sampling frequency, acceptance criteria and tolerances. Easy checklists should be developed to assist the construction inspectors in assessing conformance to all testing requirements and to ensure proper record keeping. Examples of checklists are provided in Section 2.2.7. Following are the steps required to develop QC procedures for testing and inspection:

1. Study the plans and specifications to identify all testing and inspection requirements for the project.
2. Assemble relevant contract documents needed to determine standards to be met for each test or inspection.
3. Develop any necessary checklists and train inspection staff.
4. Monitor for compliance to specified standards to be met according to the plans and specifications for the following:
   a. In-process tests and inspections
   b. In-plant tests and inspections
   c. Receiving inspections
   d. Final testing and inspections
5. Record results of required tests, inspections and observations in a timely manner on standard forms.

2.2.2.7 Maintenance of Measuring and Testing (M&T) Equipment

1. Establish a calibration and maintenance program for all M&T equipment used at the work site under the control of the field staff. The program may include specific contractual requirements, industrial or national standards and guidelines, or M&T equipment manufacturer's recommendations.
2. Document actions taken to calibrate and maintain testing equipment used and controlled by the work site inspection staff.
3. Obtain acceptable calibration and maintenance documentation for testing the subcontractor's M&T equipment.

2.2.2.8 Certification of Trade Workers

Monitor compliance for contractual requirements relating to the qualifications of trade workers performing project work, such as specified licenses and certifications. Monitor for compliance with mandated training programs for the contractor's staff.

2.2.2.9 Identification of Nonconforming Work

1. Review for compliance with specified procedures for identification and documentation of nonconforming work.
2. Evaluate and resolve remedial actions according to the options allowed in the plans and specifications such as the following:
   a. Reworking to meet requirements.
   b. Acceptance of work with or without repair.
   c. Use of materials or products at an alternative application or location.

2.2.2.10 Implementation of Corrective Actions

Initiate and monitor corrective actions as governed by the applicable provisions of the plans and specifications:

1. Monitor corrective actions for effectiveness.
2. Proactively investigate causes for nonconformance and formulate remedial or alternative processes to prevent recurrences.
3. Implement and document process changes resulting from corrective actions.

2.2.3 Considerations Related to Performance and Administrative Services

Review the plans and specifications for specific obligations related to the following categories.

2.2.3.1 Claims and Change Orders

1. Implement specified procedures for handling and resolving claims, requests for extra compensation, time extensions and change orders.
2. Conduct a timely analysis of claims and change order requests, and formulate clear and concise recommendations for their resolution.
3. Identify early potential claims and their impact on project costs and schedule. Formulate strategies for limiting claims.

2.2.3.2 Shop Drawings

Implement specified procedures for the handling of shop drawings. Monitor and facilitate the timely review of these documents by the proper party, including documentation of the process.

2.2.3.3 As-Built or Record Plans

Monitor the performance of contractual requirements for compiling and maintaining a current and updated record set of contract drawings and specifications. The record set may be compiled and produced by the contractor or by the owner's representative field staff, as contractually specified. Identify the reason for field changes in a separate record, and document any time or cost implications.

2.2.3.4 Coordination of Construction Activities

1. Schedule and conduct progress meetings, prepare agendas for meetings, and distribute memorandums of meetings to all attending parties. Identify issues requiring follow-up action. Designate the action party, and set time limits for the requested action. Monitor coordination of activities between the primary contractor and its subcontractors.
2. Review the contractor's work schedule. Identify any schedule slippage and review remedial actions proposed by the contractor to meet the approved schedule.
3. Monitor coordination between the contractor and its subcontractors and impacted agencies, companies and jurisdictions.

2.2.4 Record-Keeping Considerations

Sufficient documentation and records shall be accumulated to provide objective evidence that the construction process was performed in accordance with accepted engineering practice and with contractual requirements. The documentation should include not only the final design documents, such as drawings and specifications, but also all construction records and any communications, instructions and directives that have a direct bearing on the project.

A record-keeping system should be established prior to starting the project. The system, at a minimum, should be able to do the following:

1. Organize project files according to a mandated file index system or one developed for the particular project. Maintain the filing system to permit the timely and accurate retrieval of documents.
2. Establish and maintain separate files for documents to indicate the compliance with the QC system for the project. Records that document adherence to the provisions of the plans and specifications include the following:
   a. Inspection logs, daily inspector's reports and diaries
   b. Test data, including mill tests and certifications
   c Qualification reports
   d. Validation and calibration reports
   e. Material review reports
   f. Batch plant records
3. Prepare correspondence on a timely basis. Log incoming and outgoing correspondence. Log general complaints from the public, and document environmental issues arising from the general public and governmental agencies. Log pending or follow-up correspondence.
4. Identify the receiving organization for project records and files at completion of project. Establish a retention time for project files.
5. Maintain at the work site's required publications, documents and other materials referred to in the plans and specifications needed to properly understand and carry out the work scope and to comply with the requirements of the owner and of those of regulatory entities and standard-setting associations.

2.2.4.1 Retention of Records

Reports and records to be retained shall be determined by the project manager and/or the department managers. Records designated for retention shall be legible, suitable for reproduction, complete and adequately identifiable to the item involved.

2.2.4.2 Subcontractor Records

Records of subcontractors shall be controlled and retained in the same manner as records of the contractor.

2.2.4.3 Permanent Storage of Records

Permanent documents designated for storage shall be stored in the project file.

2.2.4.4 QA/QC Records

A single file identified as "QA/QC Records" containing copies of all QA/QC documents shall be maintained in the project files.

2.2.5 Elements of a Project-Specific QA Plan

In the absence of an owner-directed format and content requirement, the following format and content is suggested:

Section 1 *Organizations for Quality*—Provide an organization chart and description of the quality process, who implements it, who monitors it and who has the ultimate responsibility.

Section 2 *Quality Review*—Identify the internal unit level reviewer delegated to conduct primary QA reviews, the schedule for such reviews, and the format of the reviews.

- The suggested format of the review is a brief summary memorandum outlining the highlights of the review and any recommended corrective actions to be taken. The completed checklists are to be appended to the summary review memorandum. The recipients (distribution) of the QA reviews shall be listed.
- Define the implementations of corrective actions to be taken and the required documentation needed to close out all listed corrective actions.

Section 3 *QA Records*—Define how the Project QA reviews and documentation of any completed remedial actions shall be maintained as a permanent part of the project files. Specify that additional copies shall be filed with the unit's construction service coordinator together with the minimum retention period after project close out.

2.2.6 Preparation of Project-Specific QA Checklists

After the project-specific responsibilities and duties have been identified, they can be subdivided into the following broad categories:

1. Staffing and staff qualifications
2. Contract documents
3. Project files
4. Project start-up requirements
5. Miscellaneous contractual requirements
6. Claims and change orders
7. Schedule monitoring
8. Estimates and payments
9. Construction close-out
10. Daily inspection reports
11. Materials and materials certification: general
12. Materials and materials certification: specific

For each of the first 12 subdivisions, a pro-forma QAP checklist has been prepared listing concerns generally of relevance in assessing the quality of services that the contractor is providing.

The resident engineer and the chief or senior construction inspector in conjunction must review these draft QAP checklists with the contract documents for the construction-related services. Any additional specific responsibilities imposed on the contractor in these contract documents should be added to the draft QAP checklist items listed under the appropriate subdivision. Blank spaces have been provided in each subdivision to customize the draft QAP checklist to the demands of the specific project. Add sheets as needed.

The draft checklists for materials and materials certification, in particular, are very general and are limited to just a few of the standard technical construction specification divisions. These checklists must also be augmented with the quality requirements for those materials in the project's particular contract specifications. Additional checklists should be prepared for each of the major specification divisions that are part of the particular contract and that require staff involvement in certifying, observing, inspecting, testing or assessing results.

To allow further flexibility in the arrangement of checklists, the resident engineer may wish to reorganize the checklists in accordance with the applicable paragraphs of the general and special provisions of his/her particular job.

Some owners, mostly state DOTs, require their construction services providers to formulate their own QA plan. Such QA plans are based on specific guidelines required by the owner and are generally similar to the QAP checklists that follow.

2.2.7 QAP Checklists for FRP Construction

A comprehensive QA/QC program implemented and monitored by the FRP material suppliers and the FRP installation contractors should be maintained in order to ensure quality repair. QC is the direct responsibility of the contractor and should cover all aspects of the strengthening project depending on the size and complexity of the project at hand. QA during construction is the responsibility of the owner and can be achieved through a set of inspections, measurements, and applicable tests as specified in the construction specifications. The QAP checklists provided in this section address the most important parameters in the application of FRP systems. These checklists are offered as examples and are designed to assist the owners in developing their QA requirements. They follow the construction specifications for bonded repair and retrofit of concrete structures using FRP composites.

2.2.7.1 Project Start-Up Requirements (QAPs 1 through 6)

Prior to starting construction, all contractor shop drawings should be reviewed in light of the design plans and specifications to ensure adherence to the contract documents. Any perceived conflicts should be resolved prior to starting the work. The contractor should submit a material certification and identification of all the FRP materials to be used. The quantity, location and orientation of all FRP reinforcing materials to be used should be specified. The owner should ensure that the project is adequately staffed for the complexity of the job and the approved construction schedule. The qualification of contractor personnel should be evaluated to ensure that personnel have the skills, ability and experience necessary for FRP strengthening projects.

2.2.7.2 Material Qualification and Acceptance (QAP 7)

The FRP materials should be qualified on the basis of the plans and performance specifications requirements. The contractor should provide information demonstrating that the proposed FRP material meets all design and specifications requirements such as tensile strength and modulus, durability, bond strength, and glass transition temperature. Performance tests on the supplied materials should be performed according to the QC test plan and should meet the requirements specified in the engineer's performance specifications. These tests may include measuring parameters such as the tensile strength and modulus, glass transition temperature, gel time, pot life, and the adhesive shear strength. The results from independent tests of the FRP constituent materials and laminates fabricated with them should be submitted by the contractor for approval prior to starting the work. Material property information supplied by the manufacturer or material supplier could form the basis for acceptance of the FRP materials if no testing requirements are stated in the construction specifications.

2.2.7.3 Removal of Defective Concrete and Restoration of Concrete (QAP 8)

The work under this section consists of restoring delaminated, or otherwise deteriorated, concrete on selected elements using polymer- or latex-modified concrete. Concrete restoration shall include the removal of all delaminated concrete from the area to be restored and an additional 1 to 2 in. from behind the reinforcement in delaminated areas. Any loose concrete remaining in the damaged region must be removed, leaving the member with sound concrete. Surfaces where the carbon FRP (CFRP) system is to be applied must be sound. Concrete spalls and delaminations must be repaired according to the procedure identified in the plans and specifications.

2.2.7.4 Inspection of Concrete Substrate (QAP 9)

The concrete surface should be inspected before the application of the FRP material. The surface should be prepared in accordance with the engineer's specifications. The concrete surface should be examined for surface smoothness or roughness, holes, cracks, corners, and other imperfections.

2.2.7.5 Application Conditions (QAP 10)

The ambient temperature, concrete surface, and surface dryness should conform to the engineer's specifications. FRP application should be halted if rain appears to be imminent. If rain is threatening after starting the application process, the contractor should be instructed to protect the installed areas against contact with surface moisture.

2.2.7.6 FRP Application Process (QAPs 11 through 13)

Special care shall be taken to keep all records on the quantity of mixed resin during a 1-day period, the date and time of mixing, the mixture proportions and identification of all components, the ambient temperature, the humidity, and other factors affecting the resin properties. These records shall also identify the FRP sheet used each day, its location on the structure, the ply count and direction of application, and all other useful information. Sample FRP plate specimens shall be fabricated according to a predetermined sampling plan under the same ambient conditions and procedures used to apply the FRP material to the concrete surfaces. Performance tests on these FRP specimens may be conducted as needed. The evaluation of the relative cure of FRP materials can be performed (1) at the laboratory by testing sample plate specimens or resin samples using ASTM Standard D3418 or (2) at the construction site by physically observing resin tackiness and hardness of work surfaces or retained resin samples. Visual inspection of fiber orientation and waviness may be required for specific FRP material systems, since poor orientation infers misalignment of the entire system from the angles specified in the drawings. Fiber misalignments of more than 5^{o} from the specified angle ($^{1}/_{12}$ slope) may adversely affect the provisional performance of the FRP reinforcement and should be reported to the engineer. Noncompaction of fiber sheets when multiple plies are applied can result in significant voids, sagging, and local areas of debonding, all of which will substantially affect the overall performance of the FRP system and should be reported to the engineer. Additional information is provided for precured and near surface mounted FRP systems.

2.2.7.7 Identification of Defective Work (QAP 14)

The inspection program should cover such aspects as the presence and extent of delaminations, the cure of the installed system, adhesion, laminate thickness, fiber alignment and material properties.

2.2.7.8 Postapplication—QC Tests (QAP 15)

An inspection of the FRP repair system should be conducted after the full cure. Delaminations if detected should be evaluated considering their size and number relative to the overall application area, as well as their location with respect to structural load transfer. The inspection methods may include visual assessment, acoustic sounding (i.e., hammer sounding), ultrasonics, and thermography. Tension adhesion testing of cored samples should be conducted using known methods such as those described in ACI 503R or ASTM D4541. The sampling frequency should conform to the engineer's specifications. Cored samples required for adhesion testing can also be used to determine the laminate thickness or the number of plies. Approved methods to repair FRP materials having some delaminations may be used depending upon the size, number, and location of delaminations. These repairs should be performed in accordance with the engineer's specifications. The laminate should then be reinspected following delamination repairs, and the resulting delamination maps or scan should be compared with that of the initial inspection to verify whether the repair was properly accomplished. All inspection records and test results related to the FRP material should be retained. It should include delamination repair, on-site bond tests, anomalies and correction reports, and all physical test results from the designated laboratories.

2.2.7.9 General Job Administration (QAPs 16 through 20)

QAPs 16 through 18 address general job administration conditions such us claims and change, orders, schedule monitoring, estimates and payments, and DIRs.

The checklists at the end of this section are pro-forma and must be modified to the particular project. The attached diskette provides Word files for the checklists so that users can modify the checklists.

3 IMPLEMENTING AND MONITORING THE QA PROGRAM

3.1 Implementing the QA Program

The unit manager or his/her representative shall be responsible for implementing the QA program. This may be done by way of regularly scheduled project status meetings, QC reviews, spot checks and interviews with staff, or other means as determined by the unit manager. Any deficiencies, errors or nonconformances detected shall be addressed and corrective measures instituted.

The procedure for implementing the QA program is as follows:

1. The unit manager shall review the work in progress, design documents, records and project files for conformance to established procedures and generally accepted engineering practice. He/she may question staff regarding their knowledge and implementation of the QA program and shall provide instruction and assistance in its proper applications.
2. Any deficiencies, errors or nonconformances that may affect the quality of the work shall be immediately brought to the attention of the project manager and/or department managers. Deficiencies, errors, or nonconformances of a minor nature shall be brought to the attention of the individual involved for corrective action.
3. Deficiencies in staff or facilities shall be addressed by the unit manager or referred to the corporate staff for assistance, as required.

3.2 Monitoring the QA Program

The QA manager shall be responsible for monitoring the implementation of the QA program. This may be done by way of periodic project audits, spot checks, interviews with staff, or other means as determined by the QA manager. Any deficiencies, errors or nonconformances detected shall be reported and corrective measures instituted by the project manager under the direction of the unit manager. Nonconformances should be reaudited to ensure compliance.

The procedure for monitoring the implementation of the QA program is as follows:

1. The QA manager shall periodically review projects in progress or recently completed. He/she shall review design documents, records and project files for conformance to the established procedures and general good engineering practice. He/she may question staff regarding their knowledge and implementation of the QA program and shall provide instruction and assistance in the program’s proper applications.
2. Any deficiencies, errors or nonconformances that may affect the quality of the work shall be immediately brought to the attention of the unit manager, project manager and/or department managers. Deficiencies, errors or nonconformances of a minor nature shall be brought to the attention of the individual involved for corrective action.
3. The QA manager shall review any corrective actions that have been taken and shall report instances of inadequate action or unresponsiveness to the president for appropriate action.

FORM NO. QAP 1

Project Start-Up Requirements

Project No: __________________ Project Name: ____

YES	NO	N/A		
_____	_____	_____	1.	Have the construction contract documents been preliminarily reviewed for their overall completeness, obvious errors and omissions, constructability, etc.?
_____	_____	_____		a. Have the provisions been reviewed with the field staff?
_____	_____	_____		b. Have the design engineer and the owner been advised of findings?
_____	_____	_____	2.	Have the contract documents for construction-related services between the consultant and the owner been reviewed against the construction contract documents to identify possible conflicts in imposed duties and responsibilities?
_____	_____	_____		a. Have all perceived conflicts been resolved?
_____	_____	_____	3.	Has a preconstruction meeting been held?
_____	_____	_____		a. Is the agenda for the preconstruction meeting in accordance with the owner's requirements?
______	_____	_____		b. Are minutes of the meeting in the files?
_____	_____	_____	4.	Has contractor submitted all required documents on time:
_____	_____	_____		a. Insurance certificates?
_____	_____	_____		b. Bonds?
_____	_____	_____		c. Construction inspector qualifications?
_____	_____	_____		d. Permits?
_____	_____	_____		e. Equipment calibration?
_____	_____	_____		f. Quality control plans?
_____	_____	_____		g. Material safety data sheets?
_____	_____	_____		h. Schedules?
_____	_____	_____		i. Certificate(s)?
_____	_____	_____	5.	Have accident and emergency reporting procedures and documentation been established and reviewed with the field staff?
_____	_____	_____	6.	Are all forms needed to document the construction processes and quality of the work on hand at the start of the project?
_____	_____	_____	7.	Is the project fully equipped with necessary field measuring and testing equipment?
_____	_____	_____	8.	Is the measuring and testing equipment periodically re-calibrated according to the manufacturer's recommendation?
_____	_____	_____	9.	Are calibration documents on file?

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 2
Contract Documents

Project No: ____________________ Project Name: ____

YES	NO	N/A	
_____	_____	_____	1. Is a complete set of contract documents available?
_____	_____	_____	a. Plans?
_____	_____	_____	b. Specifications?
_____	_____	_____	c. Other?
_____	_____	_____	2. Are all design changes and amendments incorporated in these documents?
_____	_____	_____	3. Are all field changes incorporated in the documents?
_____	_____	_____	4. Are “as-built” plans being updated to reflect field revisions?
_____	_____	_____	5. Have all design and field changes been signed and sealed by the design engineer?
_____	_____	_____	6. Have all design and field changes been included and approved in the change orders?
_____	_____	_____	7. Are shop drawings being logged and tracked?
_____	_____	_____	8. Are all support documents required or referenced in the construction engineering and inspection contract available on site?

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 3
Specifications Review Checklist

Project No: ____________________ Project Name: ____

YES	NO	N/A		
_____	_____	_____	1.	Are the specifications complete and clear to the extent necessary to properly specify construction and performance requirements?
_____	_____	_____	2.	Have duplications or inconsistencies between contract drawings and the specifications been eliminated?
_____	_____	_____	3.	Are proper codes, standards, processes, etc., referenced?
_____	_____	_____	4.	Are requirements for shop drawings properly specified, as to both content and timely submission?
_____	_____	_____	5.	Are new materials employed and installed in the manner approved by the manufacturer?
_____	_____	_____	6.	Is proper test and inspection documentation specified?
_____	_____	_____	7.	Are the acceptance criteria tests (tolerances, etc.) specified, and are they adequate, realistic, and in line with the ordinary construction practice?
_____	_____	_____	8.	Are provisions made for the qualification and approval of special construction processes and for the personnel performing these processes?
_____	_____	_____	9.	Are measuring and testing equipment calibration requirements and cleaning, storage and handling requirements properly specified?
_____	_____	_____	10.	Are the measurement units and the basis of payment properly specified?
_____	_____	_____	11.	Is nomenclature used in the specifications exactly as it is used on the contract drawings?

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 4
Drawing Review Checklist

Project No: ____________________ Project Name: ____

YES	NO	N/A		
_____	_____	_____	1.	Is the scope of the set of contract drawings satisfactory?
_____	_____	_____	2.	Do the structures, equipment or components satisfactorily meet the functional needs and requirements?
_____	_____	_____	3.	Has accessibility for maintenance, repair and in-service inspection been provided?
_____	_____	_____	4.	Are materials properly identified on the contract drawings?
_____	_____	_____	5.	Are the items constructible as shown? Has the normal sequencing of construction trades been followed?
_____	_____	_____	6.	Is construction phasing or staging clearly shown?
_____	_____	_____	7.	Are dimensions and tolerances correct and consistent?
_____	_____	_____	8.	Have duplications and redundancy of information, data and dimensioning been eliminated?
_____	_____	_____	9.	Are the plans signed and sealed by a professional engineer?
_____	_____	_____	10.	Are the drawings legible and reproducible?
_____	_____	_____	11.	Do the titles and drawing numbers agree with the cover sheet list of the drawings?

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 5
Staffing and Staff Qualification

Project No: ___________________ Project Name: ____

YES	NO	N/A	
_____	_____	_____	1. Is the project adequately staffed based on its complexity and the approved construction schedule?
_____	_____	_____	2. Are project personnel on the job site during contractor's operations?
_____	_____	_____	3. Are the staff members properly trained and informed regarding:
_____	_____	_____	a. Authority, responsibilities and duties of the construction inspector?
_____	_____	_____	b. General rules of project safety?
_____	_____	_____	c. Hazard communication employee training program?
_____	_____	_____	d. Specific technical inspection and testing requirements?
_____	_____	_____	e. Emergency and accident procedures?
_____	_____	_____	4. Are the names and qualifications of the contractor staff on file?
_____	_____	_____	5. Do contractor staff members have required professional or technical accreditation?
_____	_____	_____	a. Has this been verified?
_____	_____	_____	6. Does the contractor's staff include a qualified provider of first aid services?

Remarks:

Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 6
Miscellaneous Contractual Provisions

Project No: ___________________ Project Name: ____

YES	NO	N/A		
_____	_____	_____	1.	Is a copy of the fully executed bid blank in the prime contractor's file?
_____	_____	_____	2.	Is there an equal employment opportunity (EEO) compliance checklist on file?
_____	_____	_____	3.	Have the contractor's EEO policy, affirmative action and disadvantaged business enterprise (DBE) affirmative action plans been submitted?
_____	_____	_____	4.	Have the monthly EEO reports been filed?
_____	_____	_____	5.	Have all needed permits been applied for by the owner?
_____	_____	_____		a. By the contractor?
_____	_____	_____		b. Are copies of all required permits in the files?
_____	_____	_____		c. Are the conditions of each permit being adhered to?
_____	_____	_____	6.	Are environmental permits or environmental control plans required? If yes, are they included in the submittal package?
_____	_____	_____	7.	Has a traffic control plan been specified for this project?
_____	_____	_____	8.	Have local law enforcement agencies been notified by the contractor of the provisions of the traffic control plan?
_____	_____	_____	9.	Has the contractor submitted names and telephone numbers of the emergency contact personnel to all agencies involved?
_____	_____	_____	10.	Has the contractor submitted evidence of required bonding and insurance?
_____	_____	_____	11.	Are meetings with the owner on a scheduled basis?

Remarks:

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Reviewer/Date: ____________________________________

Resident Engineer/Date: ____________________________________

FORM NO. QAP 7
Material Qualification and Acceptance

Project No: ___________________ Project Name: ____

YES	NO	N/A		
_____	_____	_____	1.	Have all required samples been collected and submitted?
_____	_____	_____	2.	Are all certified mill analyses and third-party test results on file?
_____	_____	_____	3.	Are all material acceptance requirements being met?
_____	_____	_____	4.	Are the materials that have failed testing requirements disposed of according to the contract requirements?
_____	_____	_____	5.	Are “or equal” materials and equipment submitted by the contractor approved by the design engineer?
_____	_____	_____	6.	Are all certified materials properly identified according to the contract requirements?
_____	_____	_____	7.	Have all relevant documents that are needed to determine if the standards are met provided to the inspection staff?

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 8
Removal of Defective Concrete and Restoration of Section

Project No: ___________________ Project Name: ____

YES	NO	N/A	
_____	_____	_____	1. Have the perimeters of existing spalls been identified and sawcut to a minimum depth of 3/4 of an inch to prevent feathered edges?
_____	_____	_____	2. Are the limits of concrete removal for each member identified in the plans?
_____	_____	_____	a. If yes, did the contractor remove any concrete beyond the identified areas?
_____	_____	_____	b. Did the contractor obtain the engineer's approval to remove concrete beyond the identified areas?
_____	_____	_____	3. Have cracks within solid concrete greater than 0.25 mm (0.01 in.) been epoxy injected?
_____	_____	_____	4. After removal of all defective areas, did the contractor inspect and clean the substrate from any dust, laitance, grease, oil, curing compounds, wax, impregnations, foreign particles and other bond-inhibiting materials?
_____	_____	_____	5. Has all exposed steel been sandblasted clean to a near white appearance prior to concrete placement?
_____	_____	_____	6. Was mechanical anchorage of the repair material with the substrate specified?
_____	_____	_____	a. If yes, was the anchorage installed according to specifications?
_____	_____	_____	7. Did the contractor apply a bonding and reinforcement protection to all exposed reinforcement and concrete surface prior to concrete placement?
_____	_____	_____	8. Did the contractor use the approved material and method of application including manufacturer's technical specifications and formulation if applicable?

Remarks:

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Reviewer/Date: ________________________________

Resident Engineer/Date: ________________________________

FORM NO. QAP 9
Inspection - Surface Preparation

Project No: ____________________ Project Name: ____

YES	NO	N/A	
_____	_____	_____	1. Is the restored concrete surface smooth, uniform and matching the concrete component's original profile?
_____	_____	_____	a. If no, were the deviations less than 0.8 mm ($^{1}/_{32}$ in.)?
_____	_____	_____	2. Did the contractor remove form lines and sharp edges by grinding or filling with putty?
_____	_____	_____	3. Have all inside and outside corners and sharp edges been rounded or chamfered to a minimum radius of 25 mm (1 in.)?
_____	_____	_____	4. Are there any 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?
_____	_____	_____	a. If yes, have surface depressions and voids been filled and cured according to specifications?
_____	_____	_____	5. Have all cracks in the surface of concrete or the substrate wider than 0.25 mm ($^{1}/_{100}$ in.) been filled using pressure injection of epoxy in accordance with the procedures outlined in the specifications?
_____	_____	_____	a. Was any surface roughness resulting from crack injection alleviated according to specifications?
_____	_____	_____	6. Was the surface checked and cleaned of any dust, laitance, grease, oil, curing compounds, wax, impregnations, surface lubricants, paint coatings, stains, foreign particles, weathered layers and any other bond-inhibiting materials?
_____	_____	_____	7. Was the final preparation of all surfaces receiving FRP performed according to the specifications?

Remarks:

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Reviewer/Date: ________________________________

Resident Engineer/Date: ________________________________

FORM NO. QAP 10
<u>Application Conditions</u>

Project No: ____________________ Project Name: ____

YES	NO	N/A	
_____	_____	_____	1. Is the ambient temperature and temperature of concrete surface within the range of 50–95°F, or as specified by the manufacturer?
_____	_____	_____	2. Are the contact surfaces completely dry at the time of installation of FRP system?
_____	_____	_____	a. Was the moisture level measured using a mortar moisture meter?
_____	_____	_____	b. Was the moisture level less than 10% or the specified limit?
_____	_____	_____	3. Does rain appear to be imminent?
_____	_____	_____	a. If yes, stop application of the material until dry conditions are ensured.
_____	_____	_____	4. If rain is threatening after starting the application process, instruct the contractor to protect the installed areas against contact with surface moisture.

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 11
FRP Application Process (Wet Lay-Up Systems)

Project No: __________________ Project Name: ____

YES	NO	N/A	
			1. *Resin Mix*
_____	_____	_____	– Is the resin prepared according to the mix ratio and procedures recommended by the manufacturer until thorough mixing with uniform color and consistency is achieved?
_____	_____	_____	– Is the resin diluted with organic solvents? (NOT allowed)
_____	_____	_____	– Is the resin mixed in quantities sufficiently small to ensure its use within the manufacturer-recommended pot life?
_____	_____	_____	– Is the excess resin disposed of when it exceeds its pot life or begins to generate heat or show signs of increased viscosity?
			2. *Primer and Putty*
_____	_____	_____	– Is the primer applied uniformly to penetrate all surface pores of concrete substrate where the FRP system is to be installed?
_____	_____	_____	– Does the rate of application of primer follow the manufacturer's recommendations?
_____	_____	_____	– Are the ambient and concrete surface temperatures as specified in the contract drawings and recommended by the manufacturer?
_____	_____	_____	– Is the excess primer disposed of when it exceeds its pot life?
_____	_____	_____	– Is the putty, if necessary, applied as soon as the primer becomes tack-free or until non-sticky to the fingers?
_____	_____	_____	– In case of delays longer than 7 days, is the surface of primer cleaned and prepared for the putty, if necessary?
_____	_____	_____	– Does the applied putty meet the surface profile according to the contract drawings?
_____	_____	_____	– Is the excess putty, if used, disposed of when it has exceeded its pot life?
_____	_____	_____	– Are the surfaces of primer and putty protected from dust, moisture and other contaminants before applying the FRP system?
			3. *Fabric Saturation and Placement*
_____	_____	_____	– Is the saturant applied uniformly on all surface areas of concrete where the FRP system is to be installed?
_____	_____	_____	– Is the viscosity of the saturant sufficiently low, according to the manufacturer's recommendations, to fully impregnate the fiber sheets?
_____	_____	_____	– Does the rate of application of saturant follow the manufacturer's recommendations?
_____	_____	_____	– Are the ambient and concrete surface temperatures as specified in the contract drawings and recommended by the manufacturer?
_____	_____	_____	– Is the excess saturant disposed of when it exceeds its pot life?
_____	_____	_____	– Is the fiber sheet cut to the length specified in the contract drawings (typically in segments shorter than 4.6 to 6.1 m [15 to 20 ft])?
_____	_____	_____	– Is the fiber sheet placed properly and pressed gently onto the wet saturant within its pot life?
_____	_____	_____	– Is any entrapped air between fiber sheet and concrete released?
_____	_____	_____	– Is rolling done in the fiber direction for unidirectional fiber sheets?

______ ______ ______ – Is rolling done in the fill direction end to end, and then the warp direction, for bidirectional fiber sheets?

______ ______ ______ – Is there excessive force or sharp metal rollers involved that could damage the fibers? (NOT allowed)

______ ______ ______ – Is sufficient saturant applied on top of the fiber sheet as overcoat to fully saturate the fibers?

______ ______ ______ – Is there any interruption in the application of undercoat, fiber sheets, and overcoat?

______ ______ ______ – Is the above sequence repeated properly for each additional fiber sheet, with an overcoat resin 15–20% greater than a single ply?

______ ______ ______ – Is each new fiber sheet applied before the onset of complete gelation of the previous layer?

______ ______ ______ – Does the number of plies applied in a single day follow the contract drawings and the manufacturer recommendations?

______ ______ ______ – In case of several days of delay between plies, is the surface of previously cured layers of the FRP system prepared properly before applying new fiber sheets?

4. *Splice and Overlap*

______ ______ ______ – Are lap joints constructed when there is an interruption in the direction of the fibers?

______ ______ ______ – Are lap splice lengths as specified in the contract drawings, but at least 152 mm (6 in.)?

______ ______ ______ – Are lap splices staggered on multiple plies and adjacent strips, unless permitted in the contract drawings?

______ ______ ______ – Are all lap joints in the fiber directions made in a single day?

______ ______ ______ – Is there any lap joint in the transverse direction, if specified in the contract drawings?

5. *Fiber Orientation*

______ ______ ______ – Are the fibers aligned on the structural member according to the contract drawings?

______ ______ ______ – Is there any deviation in fiber alignment more than 5^{o}? (NOT allowed)

______ ______ ______ – Are fibers free of kinks, folds and waviness?

6. *Anchoring of FRP Sheets*

______ ______ ______ – Is anchorage for the FRP sheets installed according to the contract drawings, and in such a way to avoid damage to fibers or concrete?

7. *Stressing Applications*

______ ______ ______ – Are stressing hardware and procedures according to the contract drawings and the manufacturer's recommendations?

______ ______ ______ – Is the grouting pressure according to the contract drawings?

8. *Curing and Final Coating*

______ ______ ______ – Is the FRP system allowed to cure according to contract drawings and the manufacturer's recommendations?

______ ______ ______ – Is the resin chemistry field modified for rapid curing? (NOT allowed)

______ ______ ______ – Does the elevated temperature that is used for curing follow the contract drawings and manufacturer's recommendations?

______ ______ ______ – Is the FRP system protected until it is fully cured?

______ ______ ______ – Is the FRP system under full load before it is fully cured?

______ ______ ______ – Is continuous pressure applied, if necessary, for the cure of FRP system?

_____	_____	_____	– Is the surface of FRP system prepared according to the contract drawings and the manufacturer's recommendation to receive coating?
_____	_____	_____	– Are solvent wipes used for surface cleaning? (NOT allowed)
_____	_____	_____	– If abrasive cleaning is necessary, is the air pressure at the nozzle limited to avoid any damage to fibers?
_____	_____	_____	– Is the thickness of protective coating for the FRP system as specified in the contract drawings and specifications?
_____	_____	_____	– Does the final appearance match the color and texture of the adjacent concrete?

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 12
FRP Application Process (Precured Systems)

Project No: __________________ Project Name: ____

YES	NO	N/A	
			1. *Application of Adhesives*
_____	_____	_____	– Is the adhesive prepared according to the mix ratio and procedures recommended by the manufacturer until thorough mixing with uniform color and consistency is achieved?
_____	_____	_____	– Is the adhesive applied uniformly on all surface areas of concrete substrate where the precured FRP system is to be applied?
_____	_____	_____	– Does the rate of application of adhesive follow the manufacturer's recommendations?
_____	_____	_____	– Are thickness and viscosity of the adhesive layer according to the manufacturer's recommendations?
_____	_____	_____	– Are the ambient and concrete surface temperatures as specified in the contract drawings and recommended by the manufacturer?
_____	_____	_____	– Is excess resin that has exceeded its pot life disposed of?
			2. *Placement of Precured System*
_____	_____	_____	– Is the precured FRP system clean?
_____	_____	_____	– Is the precured FRP system cut to the length specified in the contract drawings?
_____	_____	_____	– Are 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 followed?
_____	_____	_____	– Is the precured FRP system placed in the wet adhesive within its pot life?
_____	_____	_____	– Is entrapped air between laminate and concrete released?
_____	_____	_____	– Is excess adhesive between laminate and concrete removed?
_____	_____	_____	– Is the FRP system left undisturbed until the adhesive fully cures?
			3. *Anchoring of Precured System*
_____	_____	_____	– Is permanent anchorage for the FRP system properly installed according to the contract drawings?
_____	_____	_____	– Are temporary clamping and shoring for the FRP system properly installed according to the contract drawings?
			4. *Grouting of Precured Shells*
_____	_____	_____	– Is the precured FRP shell around the concrete column grouted at least 24 hours after installation?
_____	_____	_____	– Does pressure grouting follow the contract drawings and the manufacturer's recommendations?
_____	_____	_____	– Does the grout have a shrinkage strain of less than 0.0005 and a compressive strength greater than 27.6 MPa (4,000 psi)?
			5. *Stressing Applications*
_____	_____	_____	– Is stressing hardware according to the contract drawings and the manufacturer's recommendations?
_____	_____	_____	– Are the stressing procedures followed according to the contract drawings and the manufacturer's recommendations?

6. *Curing and Final Coating*

______	______	______	– Is the FRP system allowed to cure according to contract drawings and the manufacturer's recommendations?
______	______	______	– Is the resin chemistry field modified for rapid curing? (NOT allowed)
______	______	______	– Does the elevated temperature that is used for curing follow the contract drawings and manufacturer's recommendations?
______	______	______	– Is the FRP system protected until it is fully cured?
______	______	______	– Is the FRP system under full load before it is fully cured?
______	______	______	– Is continuous pressure applied, if necessary, for the cure of the FRP system?
______	______	______	– Is the surface of FRP system prepared according to the contract drawings and the manufacturer's recommendation to receive coating?
______	______	______	– Are solvent wipes used for surface cleaning? (NOT allowed)
______	______	______	– If abrasive cleaning is necessary, is the air pressure at the nozzle limited to avoid any damage to fibers?
______	______	______	– Is the thickness of protective coating for the FRP system as specified in the contract drawings and specifications?
______	______	______	– Does the final appearance match the color and texture of the adjacent concrete?

Remarks:

Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 13
FRP Application Process (Near Surface Mounted Systems)

Project No: ____________________ Project Name: ____

YES	NO	N/A	
			1. *Application of Embedding Paste*
_____	_____	_____	– Is the embedding paste prepared according to the mix ratio and procedures recommended by the manufacturer until thorough mixing with uniform color and consistency is achieved?
_____	_____	_____	– Are all grooves, where the FRP system is to be placed, half filled with the paste?
_____	_____	_____	– Are voids between concrete substrate and the embedding paste removed?
_____	_____	_____	– Are the ambient and concrete surface temperatures as specified in the contract drawings and recommended by the manufacturer?
_____	_____	_____	– Is the excess paste disposed of when it exceeds its pot life?
			2. *Placing FRP Reinforcement*
_____	_____	_____	– Is the FRP bar or strip clean?
_____	_____	_____	– Is the FRP bar or strip cut to the length specified by contract drawings?
_____	_____	_____	– Is there any shearing of FRP bar or strip? (NOT allowed)
_____	_____	_____	– Is the FRP bar or strip placed at mid-depth of the groove and lightly pressed to force the paste to flow around it?
_____	_____	_____	– Is the grove fully filled with additional paste and then leveled?

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 14
Identification of Defective Work

Project No: ___________________ Project Name: ____

YES	NO	N/A		
_____	_____	_____	1.	Did you find any voids and air encapsulation between the concrete and the layers of primer, resin and/or adhesive, and within the composite itself?
_____	_____	_____	2.	Are there any delaminations between layers of composite fabric?
_____	_____	_____	3.	Are there any broken or damaged edges of the composite?
_____	_____	_____	4.	Is there any wrinkling and buckling of fiber and fiber tows?
_____	_____	_____	5.	Are there any discontinuities due to fracture of fibers, breaks in the fabric, or cracks in prefabricated material?
_____	_____	_____	6.	Are there any cracks, blisters or peeling of the surface coating?
_____	_____	_____	7.	Are there any resin-starved areas or areas with nonuniform impregnation/wet-out?
_____	_____	_____	8.	Is there any undercured or incompletely cured polymer?
_____	_____	_____	9.	Are there any incorrectly placed reinforcement configurations?

Remarks:

Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 15
Postapplication - Quality Control Tests

Project No: ____________________ Project Name: ____

YES	NO	N/A		
_____	_____	_____	**1.**	**Inspection for Debonding** Perform surface inspection for any swelling, bubbles, voids or delaminations after at least 24 hours for initial resin cure.
_____	_____	_____		Is the presence of voids and air pockets suspected?
				If yes,
_____	_____	_____		– Perform an acoustic tap test with a hard object to identify delaminated areas by sound.
_____	_____	_____		– Mark all voids and assess them in terms of size.
_____	_____	_____		– Repair voids in accordance with the procedures established in the contract drawings and specifications.
_____	_____	_____	**2.**	**Inspection for Adhesion** Perform direct pull-off test according to ASTM D4541 or ACI 503R-93 after at least 24 hours for initial resin cure.
_____	_____	_____		Are test locations representative and on flat surfaces?
_____	_____	_____		Is the number of tests performed in accordance with the number established in the contract drawings and specifications?
_____	_____	_____		Is the observed failure mode of the core specimen cohesive within concrete? Failure at the bond line at tensile stress below 1.38 MPa (200 psi) is unacceptable.
_____	_____	_____		Repair concrete area after bonding test according to the procedures established in the contract drawings and specifications.

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 16
Claims and Change Orders

Project No: ___________________ Project Name: ____

YES	NO	N/A		
_____	_____	_____	1.	Have any claims been made to date?
_____	_____	_____	2.	Has the contractor provided written notification of all claims?
_____	_____	_____	3.	Did the notifications include specifics of the claims?
_____	_____	_____	4.	Did the resident engineer acknowledge each claim?
_____	_____	_____	5.	Is a separate file maintained for each claim?
_____	_____	_____	6.	Is each claim being processed and tracked according to the requirements of the specifications?
_____	_____	_____	7.	Has the resident engineer reviewed each claim, documented findings, and made a recommendation for resolution?
_____	_____	_____	8.	Have change orders been issued for satisfactorily resolved claims? Number_______ Est. Value: $_________
_____	_____	_____	9.	Does any resolved change order affect the scope of work or lengthen the contract time?
_____	_____	_____	10.	Are there any currently unresolved claims? Number_______ Est. Value: $_________
_____	_____	_____	11.	Are there any anticipated claims?
_____	_____	_____	12.	Are there any resolved change orders as a result of field conditions? Number_______ Est. Value: $_________
_____	_____	_____	13.	Are there any pending change orders as a result of field conditions? Number_______ Est. Value: $_________
_____	_____	_____	14.	Are there any change orders related to the extra work authorized by the owner? Number_______ Est. Value: $_________

Remarks:

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Reviewer/Date:_________________________________

Resident Engineer/Date: _________________________________

FORM NO. QAP 17
Schedule Monitoring

Project No: ____________________ Project Name: ____

YES	NO	N/A		
_____	_____	_____	1.	Has the contractor's work schedule been approved?
_____	_____	_____	2.	Does the contractor's work plan match the established schedule?
_____	_____	_____	3.	Is the resident engineer meeting with the contractor on a regular basis to verify and update the work plan and schedule?
_____	_____	_____	4.	What is the current status of the contract? Contract Time Used: _______%, as of Date: ________ Work Completed: ________%.
_____	_____	_____	5.	Was the "Notice to Proceed" issued in accordance with stipulations of the specifications?
_____	_____	_____	6.	Has the contractor asked for time extensions to the contract?
_____	_____	_____		a. Are time extensions anticipated?
_____	_____	_____	7.	Are time extension requests being processed according to the provisions of the specifications?
_____	_____	_____	8.	Are time extension requests based on weather delays in accordance with documented weather conditions in the daily inspector's reports?
_____	_____	_____	9.	Is there a schedule slippage?
_____	_____	_____		a. Has the owner been advised?
_____	_____	_____		b. Is there an impact on the schedule and cost?
_____	_____	_____		c. Has the contractor formulated a "back-on-schedule" plan?
_____	_____	_____		d. Have time extensions been granted? Number ______ Total time _____days

Remarks:

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Reviewer/Date: ________________________________

Resident Engineer/Date: ________________________________

FORM NO. QAP 18
Estimates and Payments

Project No: ___________________ Project Name: ____

YES	NO	N/A	
_____	_____	_____	1. Is there back-up documentation for all pay items?
_____	_____	_____	2. Are monthly payments for quantities in agreement with the engineer's estimate of quantities for that month?
_____	_____	_____	3. Are items being paid for according to the method of measurement and basis for payment called for in the specifications?
_____	_____	_____	4. Is the mobilization item being paid according to the provisions of the specifications?
_____	_____	_____	5. Is there a separate payment item for stockpiled materials?
_____	_____	_____	6. Are stockpiled materials reverified in the following month to reconcile quantities with materials incorporated into the work?
_____	_____	_____	7. Do the records indicate when the stockpiled materials are incorporated into the work?
_____	_____	_____	a. Was a deduction made for any partial payment amount previously issued?
_____	_____	_____	b. Are equipment and material storage conditions noted on daily inspector's reports?

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 19
Daily Inspectors Reports (DIR)

Project No: ____________________ Project Name: ____

YES	NO	N/A		
_____	_____	_____	1.	Are daily inspector's reports (DIRs) current?
_____	_____	_____		a. Are contractor's equipment and labor force clearly documented on DIRs?
_____	_____	_____		b. Are contractor's hours of work logged?
_____	_____	_____	2.	Is the contract day/date correctly listed on the DIRs?
_____	_____	_____	3.	Is the owner's project number listed correctly?
_____	_____	_____	4.	Is there a DIR for each construction inspector on site?
_____	_____	_____	5.	Is the particular operation or location of work clearly identified?
_____	_____	_____	6.	Are all work quantities shown for the work performed each day?
_____	_____	_____	7.	Are the subcontractor's activities clearly documented on respective DIRs?
_____	_____	_____	8.	Is there a separate DIR for each utility, force account crew, or disadvantaged business enterprise (DBE) working on the project?
_____	_____	_____	9.	Is the DBE contractor identified as DBE on the DIR?
_____	_____	_____	10.	Are weather conditions and delays adequately noted?
_____	_____	_____	11.	Is the DIR signed and dated by the responsible supervisor?
_____	_____	_____	12.	Are DIRs written in a concise, understandable and legible manner?
_____	_____	_____	13.	Are delays on the project being specifically accounted for?
_____	_____	_____	14.	Are accidents, injuries and damages described on the DIRs?
_____	_____	_____	15.	Are unusual conditions noted (high water, lane closures, icing, etc.)?
_____	_____	_____	16.	Are disputed items of work listed on the DIR?

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

FORM NO. QAP 20
Construction Close-Out

Project No: __________________ Project Name: ____

YES	NO	N/A	
_____	_____	_____	1. Have items on the final "punch list" been accepted and closed out?
_____	_____	_____	2. Has the final estimate been prepared, including pending change orders?
_____	_____	_____	3. Have all pay item quantities on the final estimate been cross-referenced from source documents?
_____	_____	_____	4. Have the final record plans been completed in accordance with contractual requirements?
_____	_____	_____	5. Are all incorporated materials and equipment tested and certified according to the requirements of the contract?
_____	_____	_____	6. Have all contractual incentive/disincentive provisions been correctly applied and administered?
_____	_____	_____	7. Has the resident engineer followed all contractual requirements in accepting the project?
_____	_____	_____	8. Has the owner's staff completed any required inspections prior to final acceptance?
_____	_____	_____	9. Are all project files reviewed before transfer to the required receiver?

Remarks:

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Reviewer/Date: ______________________________

Resident Engineer/Date: ______________________________

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation