NCHRP

REPORT 514

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Bonded Repair and Retrofit of Concrete Structures Using FRP Composites

Recommended Construction Specifications and Process Control Manual

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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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

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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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

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

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-

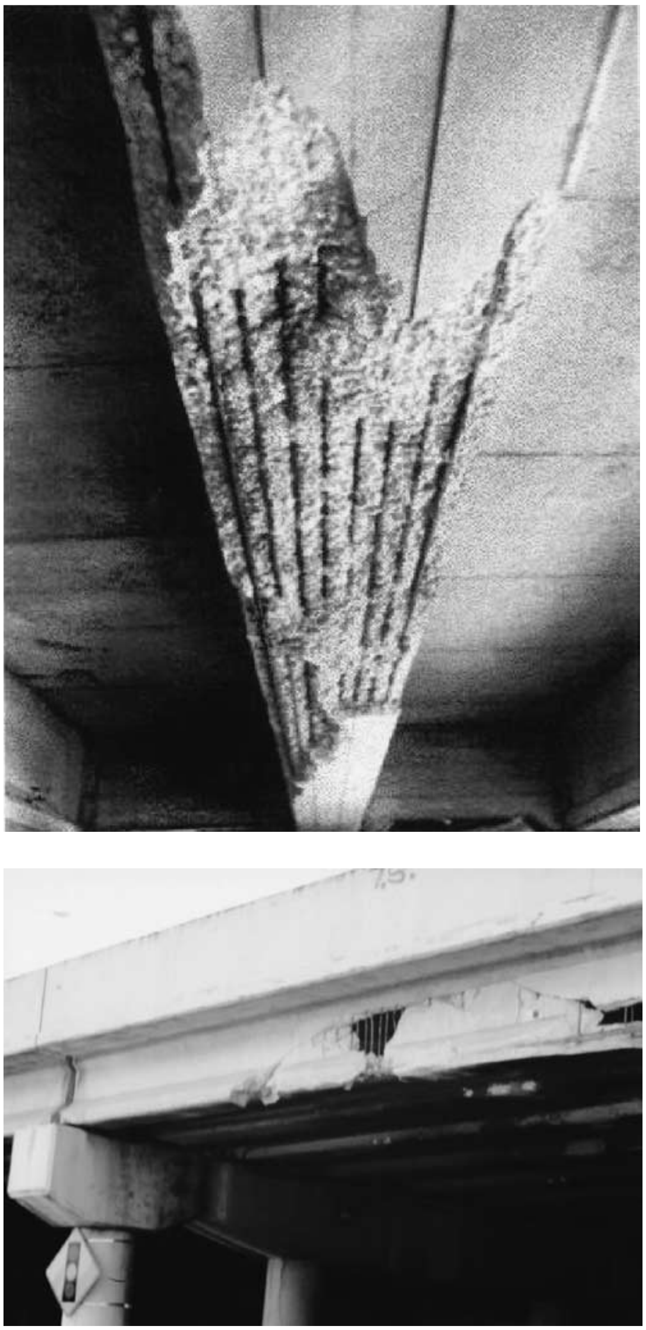

Figure 3.1. Examples of damages: corrosion (top) and vehicle collision (bottom).

Figure 3.2. Sandblasting of corroded steel.

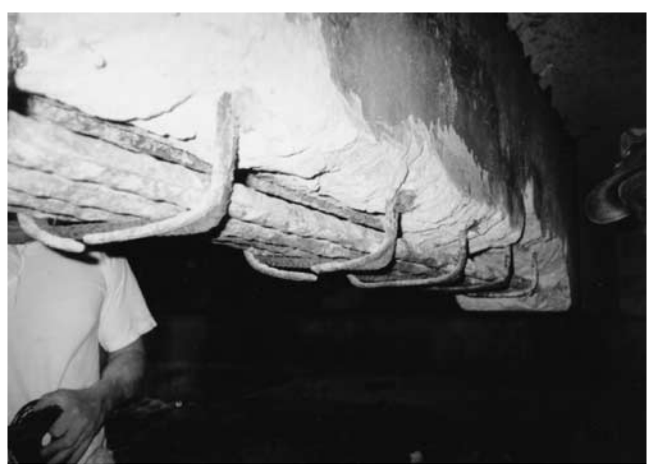

Figure 3.3. Splicing of damaged bars.

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*].

Figure 3.5. Mechanical anchorage.

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 3.7. 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.

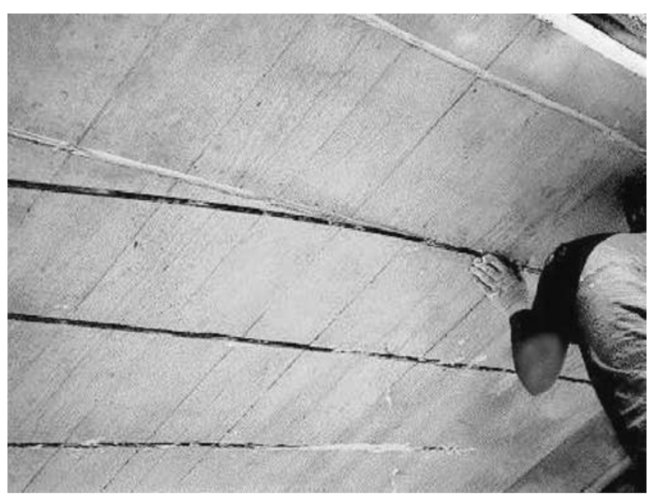

Figure 3.11. Near surface mounted rods.

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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