# NCHRP REPORT 503

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

# Application of Fiber Reinforced Polymer Composites to the Highway Infrastructure

TRANSPORTATION RESEARCH BOARD
*OF THE NATIONAL ACADEMIES*

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## 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.

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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.

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# FOREWORD

*By David B. Beal*
*Staff Officer*
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This report contains the findings of a study to develop a strategic plan for guiding the application of fiber reinforced polymer composites in the highway infrastructure. The report describes the research effort and presents the strategic plan. The material in this report will be of immediate interest to bridge engineers interested in increasing the use of fiber reinforced polymer composites.

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Fiber reinforced polymer (FRP) composite materials show great potential for integration into the highway infrastructure. Typically, these materials have long and useful lives; are light in weight and easy to construct; provide excellent strength-to-weight characteristics; and can be fabricated for “made-to-order” strength, stiffness, geometry, and other properties. FRP composite materials may be the most cost-effective solution for repair, rehabilitation, and construction of portions of the highway infrastructure. They can strengthen bridges without reduction of vertical clearance, and they can be applied in severe exposure environments that may have resulted in the deterioration of the original structure. FRP composite decks may be used to extend the life of girder-system bridges because their low dead weight allows for an increase in live-load carrying capacity.

Despite these beneficial characteristics, widespread application of FRP composites to the highway infrastructure has been slow and uneven. Although much research has been conducted on the application of FRP composites to the highway infrastructure, only a small portion has resulted in actual applications in roadway systems. The objective of this project was to develop a comprehensive and balanced strategic plan for guiding the implementation of FRP composite materials in the highway infrastructure. This objective has been accomplished with a strategic plan containing 11 prioritized elements. The plan is supplemented by white papers describing the state of the art of seven applications of FRP composite materials. Action plans for successfully implementing the applications are also provided. The strategic plan and white papers provide a road map for the development of FRP specifications for bridges and other highway applications.

This research was performed at the University of Delaware with the assistance of Wilkins Aquino and Neil Hawkins of the University of Illinois, Scott A. Sabol of Vermont Technical College, and Thomas B. Deen, consultant. The report fully documents the research leading to the strategic plan. The strategic plan and white papers are included as appendixes to the report.

# CONTENTS

# APPLICATION OF FIBER REINFORCED POLYMER COMPOSITES TO THE HIGHWAY INFRASTRUCTURE

## SUMMARY

The highway infrastructure has been deteriorating for many years, a result of sometimes harsh environmental conditions, heavy loads, insufficient maintenance, and, frequently, unintentionally damaging maintenance practices (e.g., the use of sodium chloride for winter maintenance, which results in corrosion of rebar—both bare rebar and rebar protected with epoxy coatings—as well as the corrosion of steel beams). In addition, high traffic volumes, tight construction budgets, and challenging roadway construction areas have put a strain on the ability of conventional materials to meet the public need for rapid construction, long-lasting structural components, and lightweight, easily constructed facilities. Fiber reinforced polymer (FRP) composite materials, which have been used for some time in the aerospace and military communities, have been perceived as a potential solution to some of the highway community's infrastructure needs because FRP's strengths mesh with the shortcomings of several traditional materials. However, despite sporadic attempts to jump-start the application of FRP composites to the highway infrastructure, thus far, insufficient progress has been made in determining whether the technology really holds the promise that many believe it does. More progress also has to be made in determining how FRP composites can best be deployed.

During the past decade, a significant amount of exploratory and basic research has been conducted in the United States and abroad on the use of FRP composite materials for highway infrastructure applications. Throughout the United States, a number of field demonstration projects have been conducted. Despite the considerable amount of work that has been done, however, no comprehensive effort has been undertaken to critically evaluate the growing database of knowledge, identify the most promising applications for this innovative class of materials, and develop a systematic plan for implementation of these materials. The objective of NCHRP Project 4-27 was, therefore, to look at the applicability of FRP to the highway infrastructure and to develop a comprehensive and balanced strategic plan for guiding the implementation of FRP composite materials in the highway infrastructure. More specifically, the strategic plan was to provide a road map for the development of FRP specifications for bridges and other highway applications.

The deteriorating transportation infrastructure is a large-scale national problem. It has been widely reported that approximately 28 percent of America's 600,000 public bridges are either structurally deficient or functionally obsolete (American Association of State Highway and Transportation Officials, 2002). This problem has created an urgent need for

effective means of structural repair, rehabilitation, and replacement. Increased load-carrying requirements; material degradation (e.g., corrosion, cracking, and spalling); design deficiencies; and in-service structural damage are among the many factors causing structural deficiency. Because of their many beneficial characteristics, FRP composites represent a new and promising solution for a variety of problems.

FRP composite materials have a high strength-to-weight ratio and are generally not affected by the harsh highway environment (they do not corrode, and they have excellent fatigue resistance). With increased use, FRP composite materials can have acquisition costs competitive with those of traditional construction materials while offering significant potential for reducing overall life-cycle costs. Additionally, FRP composites are very light weight, and the construction techniques used for FRP composites can greatly speed the construction or repair process, offering significant savings in costs for both the owner-agency and the user of the transportation system. Finally, through careful selection of the fibers and resins used to manufacture FRP composites, tailoring of the fiber architecture, and selection of the appropriate manufacturing technique, FRP composites can be fabricated with the desired structural properties and geometry.

In addition to bridges, other highway applications may benefit from FRP composites. For example, their light weight may be useful in variable message signs (VMSs) as well as the mast-arm supports that carry them. Currently, heavy VMSs are causing fatigue problems for their supports, and the use of FRP composites could mitigate such concerns. In addition, FRP composites in roadside barrier ("crash cushion") applications may become even more important. The ability to use FRP composites in modular construction, coupled with their light weight, makes these materials a potential alternative to current structures that rely on the crushing of steel to absorb energy.

The path to implementation and widespread application of FRP composite materials in the highway infrastructure includes (1) identification of the needs of transportation agencies and the appropriate applications of FRP composites; (2) establishment of the important engineering properties and structural behavior; (3) identification of appropriate ASTM tests for determining these properties; (4) development of AASHTO design specifications for the use of these materials; (5) development of guidelines and procedures for inspection and maintenance of FRP composite structures; and (6) development of the documentation and training necessary for widespread understanding of this technology by the engineering, fabrication, and construction industries. A cohesive strategic plan is needed to effectively accomplish this implementation.

Under NCHRP Project 4-27, the state of the art of FRP composite material applications in the highway infrastructure was evaluated through conducting a literature search and distributing a questionnaire to the members of the AASHTO Highway Subcommittee on Bridges and Structures. The recommendations presented in this research report are based on the results of the literature review, the questionnaire, and—perhaps more importantly—the research team's research experience and their personal interactions with the bridge and FRP communities. The report discusses the answers to three questions related to strategic planning:

1. Where are we today?
2. Where do we want to be tomorrow?
3. How do we get there?

The major barriers to implementing applications of FRP composite materials in the highway infrastructure have been identified as the following:

- Practicing bridge engineers' lack of knowledge of FRP composite materials,
- Cost,
- No simple bridge-specific material specifications,

- No prescriptive bridge design provisions,
- No easy and reliable inspection and repair procedures, and
- No clear signal of intent or encouragement from government agencies.

A draft strategic plan was developed to address removing these barriers to FRP implementation (see Appendix C). The plan also addresses a more deep-rooted issue, that is, that the need to improve engineers' understanding of FRP outweighs and is more immediate than the need to focus on deployment and implementation. (However, it is recognized that deployment of FRP technology will help to increase understanding of this technology.)

The draft strategic plan consists of 11 elements necessary to achieving more widespread understanding of the application of FRP composite materials to the U.S. highway infrastructure. It is hoped that this enhanced understanding will provide the foundation for successful deployment of the technology. The 11 elements of the draft strategic plan are as follows:

1. Buy-in from all strategic plan participants;
2. Acceptance, implementation, and revision of the strategic plan;
3. The means to oversee and manage the strategic plan;
4. A study of the relative costs of FRP versus traditional materials;
5. A database of practical infrastructure-based FRP knowledge;
6. Generic bridge-specific material specifications;
7. Generic bridge-specific design and evaluation methodologies;
8. Generic bridge-specific inspection and repair methods;
9. Training on FRP composite materials for practicing engineers;
10. Education on FRP composite materials for graduate civil engineers; and
11. Continuation of FHWA's Innovative Bridge Research and Construction (IBRC) program.

In the draft strategic plan, information on the following topics is given for each of the 11 elements:

- Background and description,
- Lead participants from the highway community,
- Specific tactics (action items) to implement the element,
- An approximate schedule for initiation and completion (shown in months, with the starting time being completion of NCHRP Project 4-27 or endorsement of the overall strategic plan by AASHTO),
- Resource requirement estimates (e.g., time, funding, and other) to implement the element, and
- Performance measures for the element (including benchmarks when appropriate).

Presented in Appendix D are white papers discussing five applications of FRP composites that were selected to be moved forward in subsequent tasks. The five applications are the following:

- Retrofitting concrete components,
- Retrofitting steel components,
- Seismic retrofit of bridge piers,
- Bridge decks for special applications, and
- Internal reinforcement for concrete.

Other applications of FRPs, such as highway guiderails and signs, were considered, but either did not have the potential for high payoff from switching materials or faced technological challenges greater than the applications listed above.

SECTION 1

# EVALUATION OF FIBER REINFORCED POLYMER COMPOSITE TECHNOLOGY

## BACKGROUND

To enable evaluation of the state of the art of fiber reinforced polymer (FRP) composite material applications in the highway infrastructure, a literature search was conducted, and a questionnaire was distributed to the members of the AASHTO Highway Subcommittee on Bridges and Structures. The evaluation of FRP technology presented here is based on the results of the literature review, the questionnaire, and—perhaps more importantly—the research team's research experience and their personal interactions with the bridge and FRP communities. Based on the evaluation, certain gaps in knowledge have been identified and are discussed below (see the section titled "Where Are We Today?"). Filling these gaps is, in part, the focus of the elements in the draft strategic plan developed under this project. There appears to be a fundamental gap in basic understanding and acceptance of the behavior and benefits of FRP technology. More specific sub-gaps include issues such as limited understanding of long-term behavior, the absence of commonly accepted design guidelines or performance measures, and the lack of a broad-based group with an established and accepted leadership role on behalf of all constituencies related to FRP.

## RESULTS OF THE LITERATURE SEARCH

A traditional search of the published literature on FRP composites for the highway infrastructure was conducted. The literature search identified papers published in major civil-engineering journals and conferences. One of the sources used for this search was TRB's Transportation Research Information Service (TRIS), which is the official repository of all transportation-related research documentation in the United States.

In addition to traditional sources for literature searches, a Web-based search was conducted using various search engines. Web sites of academic institutions, associations, corporations, government agencies, and suppliers were reviewed. The Web-based search allowed a more comprehensive assembly of documented material both in the United States and overseas.

### Early Research in FRP Composite Applications in Civil Infrastructure

Some of the first work on applications of FRP composites to civil structures was performed by Professor Urs Meier at EMPA (Swiss Federal Laboratories for Materials Testing and Research) in Switzerland in the 1980s. Since then, numerous research studies have been conducted throughout the world exploring potential applications of FRP composites. Several researchers have written survey papers discussing promising applications of FRP composites for a variety of civil structures (Ballinger, 1991, 1992; Bank, 1992; Head, 1992; McCormick, 1988; Measures, 1992; Sotiropoulos and Ganga-Roa, 1990). In addition, a series of conferences in the United States, Canada, Europe, and Japan has focused on the broad subject of FRP composite applications to civil structures and served as a showcase for the various research activities being conducted in this area. In this work, FRP composites have been considered for repair and strengthening as well as for use in new structures. Although much of the early work concentrated on the mechanics of FRP composite applications, and the applications encompassed the complete range of civil infrastructures, the early research set the stage for today's applications.

### Innovative Bridge Research and Construction Projects

Possibly the most recent and fertile source of information on actual field applications involves the Innovative Bridge Research and Construction (IBRC) projects. Through the Transportation Equity Act for the 21st Century legislation, the IBRC began in Fiscal Year (FY) 1998 (because of timing, project selections for FY 1998 and FY 1999 were combined in the first round of awards). The IBRC program provides direction and funding to help transportation agencies defray the cost of incorporating innovative materials and materials technologies in bridge repair, rehabilitation, replacement, and construction. The program goal is to determine the impact that high-performance materials and novel construction techniques can have on reducing maintenance and life-cycle costs.

Since the inception of this federal program, 235 projects have been awarded (see ibrc.fhwa.dot.gov/index.htm). Among these projects, 116 (roughly 50 percent) involve the application of FRP composites. In the first year alone (FY 1998–1999 combined), 37 of the 60 projects involved FRP composites. The areas in which FRP composites have been or are being applied include

- FRP Decks and Miscellaneous (67 applications),
- FRP Rebar (12 applications),
- FRP Tendons (5 applications),
- FRP Laminates (27 applications), and
- FRP Glulams (5 applications).

Although the experiences gained from these ongoing and recently completed projects are relatively undocumented, in the years to come, they should provide a wealth of information regarding what worked well and what did not. For all of the applications described in the sections that follow, the most significant remaining question involves long-term durability. Since the earliest field applications in the United States were performed in the early-to-middle 1990s, it is not yet possible to judge their long-term success. Because of the high initial cost of FRP composites, future applications beyond demonstration projects will depend on proof that they do actually yield beneficial life-cycle costs. Although this will take some time to show, the suite of IBRC projects presents the opportunity to do so. One of the gaps in knowledge that is not yet being addressed sufficiently through the IBRC program appears to be the provision of clear descriptions of the performance measures appropriate for FRP applications, FRP application benchmark levels, and the actual performance of FRP applications vis-à-vis those benchmarks in both the short and long term after implementation in an IBRC project.

### Major FRP Composite Application Areas

Based on the results of the literature search, the various highway-related applications of FRP can be divided into five categories:

- Repair and retrofitting (laminate applications),
- FRP composite reinforcement (rebar and tendons),
- Seismic retrofitting,
- FRP composite bridge decks and superstructures, and
- Unique applications.

Because the overall objective of this project was to identify the most promising applications for FRP composites and to develop a strategic plan that would best enable them to be implemented, the results of the literature review focus on infrastructure applications. One very important issue regarding the eventual implementation of FRP composites involves FRP material and design codes and specifications. An ongoing FHWA research project, "Material Specifications for FRP Highway Bridge Applications" (contract DTFH61-00-C-00020), is dealing directly with this issue. The results of this project will be very useful in answering the many materials and specifications questions. NCHRP Project 4-27 does not duplicate the efforts of the FHWA project.

#### *Repair and Retrofitting*

Some of the first work involving applications of FRP composites to civil structures involved the repair and retrofitting of concrete structures using externally bonded FRP composites. This technology is fairly mature; extensive research results exist on bond performance, creep effects, ductility of the repairs, fatigue performance, force transfer, peel stresses, resistance to fire, and ultimate strength. Today, there are numerous manufacturers of FRP composite systems for repair and retrofitting. Carbon, glass, and aramid plates and sheet systems are readily available, and the predominant application for retrofit involves externally bonding the FRP composites to concrete elements such as girders and pier caps to increase flexural capacity (column wrapping will be discussed in the seismic retrofit section). Guidelines for the design and application of these materials for flexural retrofit of concrete elements are available from the manufacturers. American Concrete Institute (ACI) Committee 440 has developed *Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* (2002). This manual can serve as a model for other FRP composite specifications.

Numerous IBRC projects have been or are being conducted that involve externally bonded FRP composites to increase the flexural capacity of concrete elements (FRP laminate applications). Throughout the world, there are hundreds of installations of this type. They have proven to be effective in enhancing the strength and stiffness of existing elements, with few signs of problems.

In addition to flexural strengthening of concrete elements, externally bonded FRP composites have been used to increase the shear capacity of concrete members. Retrofit applications aimed at controlling cracks and preventing spalling by using externally bonded FRP composites have also been conducted. Further studies have investigated the use of the bonded FRP composite to inhibit corrosion in offshore bridge piers.

Although the majority of the work has involved retrofitting of concrete bridges, recent work at the University of Delaware, the University of Nevada–Reno, and the University of Minnesota has focused on the application of FRP composites to retrofit steel bridge girders. During the summer of 2000, a steel girder of a bridge on I-95 in Newark, Delaware, was strengthened using bonded carbon-fiber plates. The durability of the repair is now being studied. Finally, IBRC Project OR-00-02 involves the strengthening of steel deck stringers. In this project, the Sauvie Island Bridge in Portland, Oregon, is being rehabilitated. The three-span steel truss bridge (600 feet in length) is made up of two deck trusses and one through truss. In the repair, FRP composite panels will be bonded to over-stressed longitudinal steel deck stringers.

*FRP Composite Reinforcement*

A primary cause for the deterioration of concrete bridge elements—decks, girders, columns, pier caps, and piers—is the corrosion of steel reinforcement. Because FRP composites are corrosion resistant, one very attractive area for their implementation involves using them to replace steel reinforcement. FRP composite rebar and FRP composite strands (or tendons) have been developed and are available from various manufacturers. In addition, two-dimensional and three-dimensional FRP composite grid reinforcement is available. Review of the literature has shown that in addition to numerous laboratory studies, several bridges have been constructed that use FRP rebar (for both flexural and shear reinforcement) and FRP strands for prestressing and for stay cables. Like the area of retrofit, this area is quite mature. Most of the relevant issues have been studied extensively. These include anchorage devices, creep and relaxation, system ductility, environmental durability, fatigue performance, force transfer, response under service loads, and ultimate strength. There are 17 IBRC projects that involve rebar/tendon applications.

One related area that has received some attention is the use of FRP strands to prestress or post-tension timber bridges (primarily transverse post-tensioning of timber decks). In this application, the wood exhibits a significant amount of creep, and the low modulus of the FRP strand is beneficial. Because of the low modulus, the loss of post-tensioning force is minimized when the wood creeps. Post-tensioning of steel bridges to increase live-load capacity has also been investigated.

In dealing with the various issues critical to the successful field application of FRP rebar and strand, several challenges have been uncovered. One major drawback in this application is that FRP composites loaded in tension behave linear elastically to failure. This means that concrete elements reinforced with FRP rebar will not necessarily exhibit the same ductile failure mode of steel-reinforced elements. Another issue relates to the lower modulus of the FRP reinforcement (especially if glass rebar is used). This can lead to greater serviceability problems including increased deflections and larger crack widths under service loads. With regard to prestressing applications, the anchorage details are critical. FRP strands are more difficult to grab, and a considerable amount of research has been conducted to develop systems that will allow the strands to be safely stressed. One important advantage of the FRP strands for stay cables and suspension cables is the significant reduction in weight.

*Seismic Retrofitting*

Another area that has received considerable attention is that of seismic retrofitting of concrete bridges using FRP composites. The primary application is column wrapping. This procedure, which can be used in place of steel jackets, provides additional confinement for the column. This leads to additional column ductility and can also enable rebar splices with insufficient laps to more fully develop.

Extensive laboratory investigations have been conducted, and several manufacturers have products that are being marketed for this application. The area is again quite mature, with the California Department of Transportation having a prequalification program that several FRP composite manufacturers have passed. Manufacturers, ACI Committee 440, and the International Conference of Building Officials have developed design and application guidelines. Several states have conducted field projects involving column jacketing using FRP composites. Some of the field applications in California were applied prior to the Northridge earthquake. Thus far, FRP composite jacket applications have performed well.

It should be noted that column wrapping could also lead to increased axial capacity. Although this is not the objective in a seismic wrapping application, it can be used as a retrofit technique for column strengthening.

*FRP Composite Bridge Decks and Superstructures*

Since the mid-1990s, several vehicular bridges have been built in the United States using lightweight FRP composite decks and slabs. These FRP composite decks and slab bridges offer several potential advantages, including the following:

- **Reduced Weight**—The reduced deck dead load allows the bridge to carry increased live loads.
- **Environmental Durability**—FRPs are corrosion resistant and therefore should not be affected by road salts and chlorides from seawater. As a result, the life-cycle costs of FRPs are expected to be lower than those of traditional materials.
- **Speed of Installation**—Because FRPs are light weight and deck sections can be preassembled in the factory, they can be installed in considerably less time than it would take to build a traditional bridge or bridge deck.

Of the FRP bridges built to date, some use FRP decks which are placed on steel girders or steel floor beams (when used as a slab on an existing truss). In other cases, the bridges are essentially slab structures with a slab that is entirely made of FRP composite (typically short span bridges). In one case, the FRP deck is supported by concrete edge girders.

Many of these bridges were constructed as demonstration projects to see how well FRP composite decks or superstructures would perform. In almost all cases, the FRP composite manufacturers subsidized the cost of the FRP composite components to eliminate the high “first-cost” barrier. In many cases, the FRP decks replaced deteriorated steel-reinforced concrete decks. In a few cases, the lightweight sections enabled live-load postings on older truss structures to be relaxed because of the weight reductions associated with the FRP composite. The use of FRP decks for moveable bridges has similar benefits. In this case, the cost of the machinery needed to lift the bridge deck can be greatly reduced. In all cases, the resistance to corrosion is a benefit, as life-cycle costs should be reduced.

Most of the decks used to date have been made out of either pultruded sections (e.g., honeycomb-shaped, trapezoidal, or double-web I-beams) or slabs made using a vacuum-assisted resin infusion process. Several have been made by hand with a wet lay-up process. Most of the bridges have a thin polymer concrete wearing surface, although sometimes asphalt is used. Various amounts of testing have been performed in order to design each of these bridges; many of them have been load-tested in the field, and/or they are being evaluated using long-term monitoring systems. One issue that has yet to be addressed involves guardrails. No crash-test-approved guardrail attachment system or fully FRP composite guardrail system exists. Studies have been initiated through ongoing IBRC projects to investigate connections that will enable traditional guardrails to be safely attached to the FRP decks. The FHWA Web site (ibrc.fhwa.dot.gov/) provides a complete list of FRP bridge-deck and FRP bridge projects funded through the IBRC. The following are notable FRP bridge decks and FRP bridges constructed in the United States:

- INEEL Bridge, Idaho (1995);
- No-Name Creek Bridge, Kansas (1996);
- Magazine Ditch Bridge, Delaware (1997);
- Laurel Lick Bridge, West Virginia (1997);
- Wickwire Run Bridge, West Virginia (1997);
- Tech 21 Bridge, Ohio (1997);
- Tom’s Creek Bridge, Virginia (1997);
- Washington Schoolhouse Road Bridge, Maryland (1998);
- Bridge 1-351, Delaware (1998);
- Milltown Bridge, Delaware (1998);
- Wilson’s Bridge, Pennsylvania (1998);
- Bennet’s Bridge, New York (1998);
- Laurel Run Road Bridge, Pennsylvania (1998);
- Crawford County Bridges (2), Kansas (1999);
- Woodington Run Bridge, Ohio (1999);
- Greensbranch Bridge, Delaware (1999);
- Bentley’s Truss Bridge, New York (1999);
- Schroon River Truss Bridge, New York (2000);
- Market Street Bridge, West Virginia (2000);
- Kings Stormwater Canyon Bridge, California (2000);
- Salem Avenue Bridge, Ohio (2000); and
- Westbrook Road Bridge (1st of Ohio Project 100), Ohio (2000).

The last two projects are worthy of additional comment. First, several different FRP composite deck sections were installed on the Salem Avenue Bridge (SR-49) in the City of Dayton (Henderson, 2000). This project is part of the IBRC program (Project OH-98-05), and the Ohio Department of Transportation is conducting studies on the effectiveness of the various FRP deck panels that were used to replace the existing concrete deck (the bridge was originally built in 1952). The new bridge, which is 96 feet wide and 684 feet long, originally consisted of four different fiber deck material sections manufactured by separate companies; because of inadequate performance, two of the deck systems have since been removed and replaced with a concrete deck. The Salem Avenue Bridge, which crosses the Great Miami River, carries six lanes of traffic with an average of 30,000 vehicles per day in and out of the city. Results of this pilot project are providing very useful information regarding the application of lightweight FRP deck panels for the replacement of deteriorated concrete decks. Issues such as appropriate detailing and quality assurance/quality control (QA/QC) of the constructed project have come to light. Sharing of information among bridge owners on successes and failures can increase knowledge on the appropriate application of FRP materials.

More recently, Ohio initiated Project 100, a statewide initiative of the National Composite Center to extensively introduce FRP composite material technology as a supplement to conventional concrete-and-steel bridge-deck construction. Martin Marietta Composites is the contractor for the project, which is now in Phase Two.

One bridge that has not yet been built, but that has received much attention is the I-5/Gilman Advanced Technology Bridge in La Jolla, California. This cable-stayed bridge, made entirely of FRP composite, will be 450 feet long by 48 feet wide, carry two 12-foot lanes of vehicular traffic, and have two 8-foot bike lanes, a walkway, and utility lines. Among many FRP composite components, the bridge will have girders and pylons made of carbon fiber reinforced polymer (CFRP) composite tubes filled with concrete, an FRP deck, and FRP stay cables. The project is currently funded through the IBRC program (Projects CA-98-01, CA-00-01, and CA-01-01). As with many large-scale demonstration applications, especially those using rapidly evolving technologies, issues related to specific final designs and details for the I-5 bridge (among other reasons) resulted in delays of its actual deployment.

From the results of field load tests, ongoing monitoring, and bridge inspections, it appears that the existing FRP bridges are generally performing well. The one area of concern is the durability of the wearing surface. In several cases, significant reflective cracking has been observed. This may be due to the local flexibility of these decks under concentrated wheel loads. Furthermore, the Salem Avenue Bridge in Ohio, which employed several different FRP deck sections, is experiencing serviceability issues. These issues seem to be related to the deck joints (the problems are currently being investigated and have yet to be publicly presented).

Finally, one area that has not been adequately addressed is inspection methods for these FRP bridges (or any other FRP application). Bridge management engineers who conduct biennial inspections are not aware of what needs to be done to inspect the FRP composite components. NCHRP Project 10-64 ("Field Inspection of In-Service FRP Bridge Decks") is currently addressing this issue.

### *Unique Applications*

Although most FRP infrastructure applications fit into one of the four previously mentioned categories, a few do not. Several of these unique applications are presented here. The first is the use of FRP composites for pedestrian bridges or cantilevered pedestrian/bike paths. The following are just a few of the pedestrian bridges that have been built:

- Aberfeldy Footbridge, Aberfeldy Golf Club, Scotland (1993);
- LaSalle Street FRP Composite Pedestrian Walkway, Chicago, Illinois (1994);
- Antioch FRP Composite Pedestrian Bridge, Antioch, Illinois (1996); and
- Homestead Bridge, Los Alamos, New Mexico (1997).

In addition to these purely pedestrian bridges, Foster-Miller is currently working with a state department of transportation (DOT) to design and construct a cantilevered FRP sidewalk that can solve pedestrian/bike issues. Other unique applications include piles, stay-in-place forms, glulams, signs, grates and drains, and guiderails/guardrails. Although the number of these applications is much smaller than those in the prior categories, they represent a promising set of potential FRP composite uses.

## Codes and Specifications

Most of the field applications discussed have been designed based on project-specific research or guidelines provided by the FRP composite manufacturers. If FRP composites are to become a mainstream construction material, codes and specifications will need to be developed. Thus far, other than manufacturer-supplied design guidelines, only a few sets of codes and specifications have been developed. Possibly the first was developed by the ISBO of Southern California. This code treats laminate applications and, in particular, column wrapping. As mentioned before, ACI Committee 440 has developed *Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* (2002). Finally, the new *Canadian Highway Bridge Design Code* (2001) covers FRP in some detail. These early attempts at codifying FRP composite applications should provide the stepping-stone for introducing the technology into future bridge design codes.

Three FHWA-sponsored research projects in the area of FRP composite materials are currently underway. "Materials Specification for FRP in Highway Bridges" is being conducted at the University of Wisconsin. This project is developing physical/chemical and mechanical test-based qualifications for FRP laminates based on minimum performance targets and acceptances for FRP parts in terms of consistency in reaching targets. "Acceptance Test Specification for FRP Decks and Superstructures" is being conducted at the Georgia Institute of Technology and West Virginia University. This project is developing standards and test methods to qualify FRP-deck and deck-superstructure materials and products, to test and accept FRP decks and deck superstructures, and to exercise job-site control during construction. "FRP Prestressing for Highway Bridges" is being conducted at the University of Wyoming, Pennsylvania State University, and the University of Missouri at Rolla. This project is developing product-performance specifications for tendons, anchors, and stressing attachments, as well as design and construction specifications for beams, decks, and piles prestressed with FRP. Two NCHRP projects currently underway in the area of developing specifications for FRP composites are NCHRP Project 10-55, "Fiber Reinforced Polymer Composites for Concrete Bridge Deck Reinforcement," and NCHRP Project 10-59, "Construction Specifications for Bonded Repair and Retrofit of Concrete Structures Using FRP Composites."

## RESULTS OF QUESTIONNAIRE

A questionnaire to gather information on the application of FRP composite materials in the highway infrastructure was distributed to the members of the AASHTO Highway Subcommittee on Bridges and Structures. A brief "snapshot" of the questionnaire responses is given here.

Twenty-three responses to the questionnaire were received. In these responses, 32 projects using FRP composites were documented. They ranged from an entire two-span continuous bridge in California to a glass fiber reinforced polymer (GFRP) sidewalk addition to a steel bridge in Vermont. The types of applications reported in the questionnaire are summarized in Table 1.

The projects discussed by the DOTs who completed the questionnaire used either GFRP or CFRP. The majority of the

**TABLE 1 Fiber reinforced polymer applications documented in questionnaire**

| Application | Number Reported |
|---|---|
| Repair or Strengthening | 15 |
| Deck | 6 |
| Internal Reinforcement for Concrete | 4 |
| Seismic Retrofit | 3 |
| Other | 4 |

respondents did not specify the type of fibers used. However, from the discussion of the applications, it can be surmised that the majority used glass fibers. Culturally, there seems to be a tendency to be specific when speaking about CFRP composites. Perhaps this is due to the very high cost of CFRPs. Table 2 summarizes the responses regarding material type.

In general, the projects were reported to be successful in that the construction went well. However, the outcomes were inconclusive because the long-term durability of the FRP composite material is still to be determined in the field. There was much concern about the relatively high cost of FRP composites. The advantages of FRP composites over traditional materials cited by the respondents were that they are more durable and light weight. The disadvantage most often cited was cost. The state bridge engineers' opinions of the potential for widespread application were mixed.

The state DOTs depended heavily on academics, FRP manufacturers, and suppliers for information on FRP applications and specifications. Few, if any, general specifications are available for FRP applications to the highway infrastructure. In some cases, project-specific fabrication and construction specifications were developed.

## WHERE ARE WE TODAY? SPECIAL CHALLENGES ASSOCIATED WITH FRP IN CIVIL APPLICATIONS

Much of the excitement about FRP composites for highway infrastructure applications has been aroused not by technical stimuli but by cultural stimuli. A major source of the current excitement is not so much the result of bridge engineers looking for a new material for bridges as it is the result of FRP composite marketers looking for a new application. The end of the Cold War and the accompanying reduction in military spending influenced this search for new markets, especially among carbon fiber producers.

A second influence on the interest in introducing FRP composites into the highway infrastructure is academic researchers and their sponsoring agencies. A completely new material offers more readily apparent opportunities for proposing research than mature, seemingly exhausted, fields. The introduction of a new material into an existing field is more exciting and appealing than the refinement of traditional materials to research agencies as well. Finally, a new material is more exciting and appealing to research-funding agencies and their patrons. Agencies backed by practicing engineers such as FHWA, NCHRP, and state DOT research groups, have been more guarded in embracing exploratory research into FRP composites.

**TABLE 2 Materials documented in questionnaire**

| Material | Number Reported |
|---|---|
| CFRP | 8 |
| GFRP | 4 |
| Other | 0 |
| Not Identified | 21 |

### FRP Composites as Designer Materials

Proponents of FRP composites praise them as designer materials, capable of being tailored to any need. On the basis of demand, the designer can specify the fibers, the resins, and the architecture of the FRP composite, as well as the lay-up and fiber orientation. For widespread application of FRP composites in the bridge infrastructure, this is not necessarily a desirable attribute.

In addition to the flexibility in design of FRP composites, many of the manufacturing processes for these materials are based on patented technologies that do not traditionally work well within the open, competitive-bid nature of transportation construction. For both fibers and resins, designers must choose among many products and many manufacturers. The interchangeability of manufacturers' products is not apparent, and this seems to be intentional. Similarly, the designer must specify the internal configuration of the FRP composite—in other words, its architecture. The architecture includes the direction of the fibers and their number. The fibers can be individual fibers or mats of woven fibers.

Traditionally, a bridge engineer's choice of materials has been limited to steel and/or concrete at various respective strengths. Steel is specified by its yield strength, $F_y$, and concrete is specified by its compressive strength at 28 days, $f'_c$. Many producers and suppliers can meet the generic specifications. As noted below, most bridge engineers are familiar with material behavior needs, but not the specific attributes of various materials.

The example of structural steels for bridge applications is worth examining. About 10 years ago, bridge designers would specify bridge steels using several ASTM specifications—ASTM A36, A588, A572, and so forth—with a supplemental requirement for toughness (required for bridges but not buildings) because of the cyclical loading of trucks. To simplify this process, all of the bridge steels and the supplemental toughness requirements were combined into the single specification of ASTM A709, which includes Grades 36 through 100. Now bridge designers use a single specification for bridge steels. Even the new high-performance steel (HPS) has been included in the single simple specification as A709 Grade HPS70W ("HPS" for high-performance steel, "70" for the yield strength, and "W" for weathering steel). The specification of traditional materials is made as simple as possible.

The contrast between the current manner of specifying traditional materials and specifying FRP composite materials is dramatic. FRP composites have strength only where the designer has provided it through fiber orientation and placement. For shell-type structures and other structures in which membrane forces predominate, isotropic material properties can easily be provided. This is, in part, why FRP is so popular in the aerospace industry (another reason is the relative lack of cost sensitivity in that market). For components being touted for bridge structures, however, cost is an issue. For a cost, pultruded members, which are linear in nature, can be provided with fibers in directions other than the longitudinal direction. Nonetheless, the majority of fibers in pultruded members will be in the longitudinal direction. Built-up FRP composite components fabricated through resin transfer or adhesive joints will have planes of weakness where resin alone holds the built-up section together.

Alternative load paths are virtually nonexistent within FRP composites because the resin matrix offers little resistance to load. Bridge engineers have learned the hard way about unintended or unanticipated load paths through building steel bridges. Where transverse members—for example, cross-frame diaphragms or floorbeams—are connected to longitudinal girders through connection plates unattached to the flanges, longitudinal fatigue cracks develop in the web at the ends of the connection plates. This cracking is due to relatively small, unanticipated out-of-plane distortions. With welded steel girders, the connection plates are left unattached to avoid welding to the tension flange. Welding the connection plates to both flanges in addition to the web, as specified in Article 6.6.1.3.1 of the *AASHTO LRFD Bridge Design Specifications* (1998), prevents cracking. Although the unattached connection plate represents a weakness, the isotropic properties of steel allow redistribution of the stresses. The cracking is a serviceability problem, but has no effect on the strength.

The traditional analysis method, in which lateral live-load distribution factors are used to determine transverse load distribution, leads to an under-appreciation of load paths. Transverse load paths are implicit. Approximate methods, which uncouple longitudinal and transverse behavior, are used for all typical bridge types, even California's multi-web cast-in-place box girders.

Bridge inspectors who have inspected old, neglected steel bridges can attest to the ability of traditional materials to carry loads through unanticipated load paths. Many times, near the ends of corroded riveted girders with practically nonexistent webs, shear is carried through frame-action between the flange angles and bearing-stiffener angles. It can be difficult, if not impossible, for the bridge designer to anticipate load paths for all future eventualities, and the ability of resin alone to resist unanticipated loads is questionable.

### Bridge Designers as Generalists

Typically, traditional bridge designers have not been concrete bridge designers or steel bridge designers, but merely bridge designers, applying the appropriate material in the appropriate time and place. Bridge designers have not needed to be experts in material science to design, evaluate, and maintain bridges of steel and concrete. This is not the current situation with FRP composite materials. The current application of FRP composites for bridge structures requires a level of knowledge of FRP composite materials far in excess of that required of the traditional materials, steel and concrete.

Bridge engineers will not become FRP composite material experts, and FRP experts do not have the expertise needed to design, evaluate, and maintain bridges.

### FRP Composites as Proprietary Items

The FRP composite components currently being developed are typically patented proprietary items. The FRP composite component suppliers seem to either lack understanding of the nature of the bridge community or as yet have simply failed to change their business approaches to be compatible with the bridge community. Proprietary items are rarely specified in the building of bridges, and when they are, it is only when there is not an equal alternative.

FRP composite component fabricators have even been hesitant to allow bridge owners to witness the fabrication of the components they were purchasing. The shop inspection of steel girders, prestressed concrete girders, and all other shop-fabricated components is routine and necessary for bridge owners to ensure the quality of components that they are buying.

Bridge owners wish to have many sources for products to foster competitive pricing. For competitively bid projects, it is frequently unacceptable to have only one available source for products. Bridge owners have found that their bridges, whether built of steel or concrete, are more cost-effective if concrete-bridge and steel-bridge fabricators compete for business in their jurisdictions.

### FRP Composite Components as Replacements for Traditional Components

Many proposed FRP composite bridge applications involve the replacement of traditional components with FRP composite components. It appears that there is a broad familiarity with the literature citing reinforced-concrete bridge decks as the bridge components most likely to need replacement because of deterioration.

The replacement of existing deteriorated reinforced-concrete bridge decks with FRP decks is a viable alternative only when the concrete deck is non-composite. When the existing deck is composite, the FRP deck cannot adequately replace the compression force provided by the concrete deck in the positive-moment region. With the FRP deck in place, the composite positive-moment section will have a reduced capacity unless prohibitively expensive carbon fibers are used.

In new construction, the selection of FRP composite materials can require the use of heavier girders under the deck.

The more expensive decks and heavier traditional girders add to the already high initial costs associated with the use of FRP. This is not to say that the use of FRP with its potentially lower life-cycle cost may not eventually change the existing practice of using girders composite with the deck. If use of heavier non-composite girders with a non-composite FRP deck results in an overall lower life-cycle cost, other, less-attractive aspects of non-composite construction, such as questions about robustness, may be overlooked.

Even evolutionary enhancements to traditional materials such as the introduction of HPS require new design concepts and structural forms to fully use the new-found properties. With enhanced weldability allowing a move to grades of steel greater than 50 ksi, limit states that previously did not govern, such as deflection and fatigue, suggest new cross sections and design concepts. However, even with well-known materials such as steel, the highway engineering community is slow to accept new shapes and design concepts.

### Use of FRP Composite Materials as a High-Profile Innovation

Some bridge owners apparently have constructed or are constructing bridges with FRP composite components to demonstrate their openness to innovation. Some of these bridge owners have been quick in implementing an innovation such as FRP, yet have been slower in implementing wider-reaching innovations such as the new load and resistance factor design (LRFD) bridge code. This is interesting, in that training and software needs (which are sometimes perceived as barriers to implementation of LRFD) are equal, if not greater, for FRP applications. The innovation of changing design methodologies is transparent to lay supervisors and the public. The innovation of constructing FRP bridges is high profile. In fact, the terms *high-performance steel* and *high-performance concrete* (HPC) were coined by traditional materials producers to make traditional materials seem innovative and new. Thus, there may be some impetus to use FRP merely to demonstrate novelty and innovation rather than exploit the intrinsic advantages of these advanced materials.

### Fragmented Nature of the FRP-Producer Community

There is not a single organization representing the FRP-producer community (both material suppliers and fabricators) effectively interacting with the bridge community, in particular with the AASHTO Subcommittee on Bridges and Structures. The Market Development Alliance of the FRP Composites Industry (MDA) is moving in this direction, but has yet to establish a relationship with the bridge community that approaches the relationship of the bridge community with the organizations representing the traditional materials' industries. The example of the steel and concrete material industries is worth citing. The American Iron and Steel Institute (AISI), the National Steel Bridge Alliance (NSBA), and the Precast/Prestressed Concrete Institute (PCI) effectively interact with the appropriate technical committees (T-14 and T-10, respectively) of AASHTO's Subcommittee on Bridges and Structures.

AISI and PCI are, in effect, partners with AASHTO. Technical Committees T-14 and T-10 meet semiannually with AISI and PCI, respectively, outside of the annual meeting of the AASHTO Subcommittee on Bridges and Structures. AISI and PCI help to manage the development and maintenance of the respective design provisions for steel and concrete bridges. Although each organization tries to present its respective material in the best light, when problems need to be addressed, AASHTO and AISI or PCI work together to solve them. Neither individual FRP composite material producers nor their collective organizations have followed the lead of the traditional materials groups in working this closely with AASHTO.

Other materials, such as masonry in the buildings industry, have enjoyed stronger implementation because of coordination among code officials and industry groups. For example, The Masonry Society (TMS) and the Brick Industry Association—which serve as umbrella groups for the Portland Cement Association (PCA), the National Concrete Masonry Association (NCMA), and many others—encourage and facilitate the open sharing of product information and, perhaps more importantly, open recognition of the shortcomings of their products.

It is important to note that although materials do have specific properties of importance to their application (e.g., one would not use A992 steel in a bridge), in general, there is collective wisdom generated through experiences with materials used in the buildings industry that is translatable to the highway industry and vice versa. Groups such as AISI and PCI serve both the highway and buildings industry. Because FRP can be used in both highways and buildings, FRP producers need an umbrella "guidance group" that effectively interacts with both industries.

The FRP manufacturing and supplier community is large, with many activities in the retail (e.g., fishing poles and watercraft), aerospace, and military (e.g., anti-ballistic protection) markets. This multibillion-dollar industry (a recent estimate puts it at $9 billion) is as diverse as the steel industry (whose applications range from cans to motorcycle components to refinery equipment). However, the FRP industry as yet has not diversified into the highway market as significantly as the steel, concrete, and wood industries.

### Demonstration and Research Projects

FRP composite bridge components are not finding their way into application through competitive bidding. Without either explicit or implicit outside support from industry or government, few of the existing applications would have been realized. Most, if not all, current applications of FRP composites in the highway bridge infrastructure are the result of individual demonstration projects, sponsored by FHWA and/or state DOTs, or research projects, sponsored by research agencies (including again FHWA and/or state DOTs). Many times the true costs of FRP composites have been hidden or obfuscated. The learning curve that accompanies the introduction of *any* new technology typically produces initially higher costs; what is not yet clear is whether these initially higher costs will decline substantially with increasing use of FRP.

Applying FRP composites to the bridge infrastructure in individual demonstration projects has resulted in a quite fragmented effort, with little overlap or interaction between projects. Aside from scholarly journal articles, which typically appear long after project completion, and conference presentations, in which details are sketchy, the sharing of findings is virtually nonexistent. The projects have no continuity or common goal.

### Joining of FRP Composite Components

Components of bridge structures must be joined together in the field because of the sheer size of bridges and the limitations of shipping components over the road and railroads. Steel components are joined in the field mostly through bolted connections and infrequently through field welds. Concrete components are joined through post-tensioning or field pours.

FRP composites do not lend themselves easily to field-bolted connections. The fibers within FRP composites are continuous through the components. Fabricating a hole for a bolted connection destroys the continuity of the fibers and compromises the strength of the member at the joint. Further, the bolted connections must be bearing connections because high-strength bolts tensioned to a typical force would deform the FRP. Thus, the bearing connections would ratchet back and forth under the stress reversals of truck passages, destroying the connection. Substantial additional research and development work in the area of bolting of FRP structures is required before this can become an effective and accepted method of connecting elements.

FRP composite bridge decks have been fabricated with pockets to receive steel shear studs, similar to what is done with precast concrete bridge decks. However, in the case of the FRP composite decks, the failure mode is the deformation of the perimeter of the pocket in the FRP composite deck and not the traditional failure of the stud itself. For precast concrete decks, the pocket subsequently filled with concrete ultimately provides a monolithic concrete deck. In the case of a cellular FRP deck, the concrete-filled pocket results in a severe stress concentration in the deck, as evidenced by the deformation of the FRP pocket surrounding the concrete.

The best way to join FRP composites seems to be with adhesives. Adhesives have been used with traditional materials, but not as the source of resistance of the joint. For example, epoxies are used in wet-joints between post-tensioned segments of segmentally constructed concrete bridges. In these cases, the joint is maintained by the post-tensioning; the epoxy merely provides waterproofing. Other than suggested performance from accelerated laboratory testing, the durability of the bond in terms of maintaining the structural integrity of the joint is unknown.

### Repair of FRP Composites

FRP composites are used as armor for military applications because these materials have a great ability to absorb energy from impacts. This energy absorption is the result of much internal material damage. The damage is difficult to repair, as it is within the thickness of the material and not necessarily evident on the surface. Nonetheless, repairs are routinely made in other fields of FRP application such as marine and aerospace applications. Procedures are yet to be fully developed for highway infrastructure applications, in which components of FRP tend to be thicker.

Girders made of traditional materials can be relatively easily repaired when they are impacted by over-height vehicles. Impacted steel girders can be heat straightened. Severely bent or torn steel flanges and webs can be cut out and replaced through careful field welding of replacement, shop-fabricated, web-flange assemblies into the existing girders. Damaged concrete girders can be repaired by shotcreting spalled concrete cover and mechanically coupling any severed reinforcement. Repairing deep damage in FRP components represents a challenge, as does the whole general area of FRP repair (including the QA/QC associated with the repairs).

### Limited Data for Infrastructure-Type Applications

FRP components—for example, fiberglass boats and ladders—have a long history of successful use. Unfortunately, the vast majority of applications to date are very different from infrastructure-type applications. Most current widespread applications use sections that are relatively thin compared with the section thicknesses required for bridge structures. The data developed for the thinner sections may not be applicable for bridge-scale sections. For example, it has been found that thick steel sections, most notably large rolled-beam column sections for large buildings, have very variable properties through their thicknesses.

The high cost of carbon fibers suggests that the majority of FRP applications for the highway infrastructure will use lower-cost glass fibers. GFRP components will be governed by deflections, as they exhibit a relatively low stiffness. Thus, relatively large sections require and carry relatively low stresses. The fatigue data available for FRP composite materials are in higher stress ranges than the stress ranges expected to be exhibited by thick sections. This is another way in which the thin-section FRP data may not apply for thicker-section infrastructure applications.

### Non-Ductile Nature of FRP Composite Materials

FRP composite materials behave linear elastically to failure. If adequately braced against buckling, sections of FRP, which are relatively thin (more like steel sections than concrete sections), will fail suddenly and in a brittle manner. Admittedly, the strain at failure is relatively large.

Traditionally, bridge engineers have used materials that, if overstressed, fail in a ductile manner with much deformation and warning to users. Steel members are inherently ductile because of the linear elastic/perfectly plastic behavior of steel. For sections consisting of steel and concrete, the AASHTO specifications mandate ductile behavior by forcing steel to yield before the concrete crushes in composite steel girders, reinforced-concrete girders, and prestressed concrete girders.

One exception to the classic ductile-failure requirement currently exists in the AASHTO specifications. For the case of minimally reinforced concrete beams, the minimum amount of reinforcement to preclude rupture of the steel is waived if an over-strength of 33 percent beyond the factored demand is provided (see Article 5.7.3.3.2 of the *AASHTO LRFD Bridge Design Specifications* [1998]).

### Prescriptive Nature of AASHTO Specifications

The various AASHTO specifications and other infrastructure-related codes (e.g., American Institute of Steel Construction, ACI 318, and the National Design Specifications for Wood) have grown very prescriptive over time. The design methodologies for bridge components made of traditional materials are very regimented, with little engineer input necessary in the process. Steel girders are classified as compact or non-compact based on criteria outlined in the AASHTO specifications, with the resistance specified by explicit equations. Similarly, the resistance of concrete girders is explicitly defined by the universally accepted Whitney stress-block concept embedded in the AASHTO specifications' design equations. Practicing engineers, mindful of liability, are loath to deviate from the prescriptive provisions by using alternative resistance models or especially by designing components not covered by the specifications.

The AASHTO specifications are completely silent about components for bridge superstructures fabricated from materials other than concrete, steel, aluminum, or wood. Venturing into the use of FRP composite materials for bridge superstructures brings the potential for much unwanted liability for bridge designers.

It is worth noting that under NCHRP Project 12-42 a guideline document has been developed that is applicable to all innovative materials, to enable them to more easily become integrated into the AASHTO LRFD code in the future. The document comprises two parts: an editorial guide (so that developers of design and construction specifications use terminology that is consistent with current bridge practice) and a technical guide (that provides information on how to calibrate the resistance factors for new materials and products).

With many state DOTs moving toward a limit-states design philosophy, it is worth noting that under NCHRP Project 17-10 research was conducted to determine the feasibility and utility of drafting a new *AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals* with a section on FRP using LRFD. It was determined that there were insufficient data to perform the necessary calibrations. (Another reason for not going to LRFD was that such structures are primarily live-loaded [wind-loaded], a case in which the economies resulting from LRFD are not perceived to be as great.) However, the FRP materials are included in that AASHTO specification, albeit with very limited coverage.

The *Canadian Highway Bridge Design Code*, released in 2001, includes coverage of FRP. The coverage is relatively specific and more "performance-based" than prescriptive, but this is a strong step toward getting the material into more common bridge practice.

The use of prescriptive, "recipe-type" specifications for highway structures has been evolving with the advent of what are known as "performance-related specifications" (PRSs). Although PRSs have not made significant inroads into the bridge community, they have developed a following within the pavement community and other arenas. Essentially, a PRS might simply indicate the required performance characteristics of a structure; in the case of a pavement, that might be its smoothness (perhaps measured by the International Roughness Index) and expected life-cycle or maintenance-free (or repair-free) period of performance. The actual materials and their proportions are not specified by the owner agency, leaving contractors to develop and employ innovative strategies and technologies for achieving the desired performance.

The technical and cultural issues associated with PRSs make it improbable that such a large change in engineering design will become commonly practiced in the foreseeable future. However, using PRSs would require a different level of knowledge about materials among bridge owners. This might relieve concerns about working with newer materials, such as FRP, with which the bridge community is relatively inexperienced. It is probable that the FRP manufacturer/supplier community has operated in the context of PRS-based applications in its marine watercraft, military, and aerospace applications.

## WHERE DO WE WANT TO BE TOMORROW? REQUIREMENTS FOR WIDESPREAD UNDERSTANDING AND DEPLOYMENT OF FRP COMPOSITES

### Bridge Design Objectives

The culture of the FRP composite materials industry must adapt to the culture of the bridge community for FRP composites to be successfully implemented. The bridge community has no pressing need to adapt to using FRP composites; FRP composites are not required to design bridges. For the most part, bridge designers believe that the bridges they design of concrete, steel, and/or wood are performing adequately. The only area in which improvement may be desired is in bridge durability. FRP composites' potential for more durability and greater cost-effectiveness in terms of life-cycle costs may open the door to the bridge-construction industry.

In Article 2.5, the *AASHTO LRFD Bridge Design Specifications* (1998) define the bridge designer's objectives as follows:

- Safety,
- Serviceability,
- Constructability,
- Economy, and
- Aesthetics.

Bridges are expected to meet these objectives. For successful widespread implementation of FRP composites in bridge construction, bridges made of FRP composites must meet or exceed the expectations for bridges made of traditional materials for all of these objectives.

#### *Safety*

The first objective, safety, is the most important from the point of view of the bridge designer's responsibility to society. People know that commercial airline accidents, highway accidents, and (rarely) bridge collapses occur, but they find this unacceptable. Accordingly, a large amount of public funding is allocated to maintaining and increasing the safety of airplanes, highways, and bridges.

To date, most of the academic research into FRP composites for infrastructure applications has focused on safety. It is the easiest aspect to investigate because, for the most part, the variable of time is not studied. Further, the investigation of safety requires little understanding of the culture of bridge construction.

FRP composites exhibit great strain at failure. If designed properly, FRP composites should exhibit strength in excess of that required, ensuring structural safety. Proper design includes the consideration of buckling of thin sections in compression and out-of-plane distortion resulting in interlaminar failures.

In the case of GFRP composites, the relatively low stiffness of the material results in a relatively large section to satisfy the live-load deflection criteria for bridges. The large section is stressed only to very low levels. The margin of safety to failure is very large. At failure, the theoretical deflection of the bridge would be far in excess of the dead-load deflection plus the traditional live-load deflection limitations.

The issue of the mode of failure, however, must be addressed. FRP composites behave linear elastically all the way to failure. Components and systems of FRP materials must be properly designed so that the final failure will be the classically desirable ductile mode. Typically, hybrid design solutions, in which various materials are used to best advantage—such as contemporary cable-stayed bridges in which steel cables, concrete pylons and decks, and steel or concrete substructures combine—are the optimal solutions. Most likely, FRP composites will ultimately be used in hybrid design solutions.

#### *Serviceability*

Highway bridges, unlike aircraft, are put into service and basically ignored for intervals of 2 years between federally mandated inspections. Traditionally, bridges have been designed with this eventuality in mind. Article 2.5.2 of the *AASHTO LRFD Bridge Design Specifications* (1998) includes the following as issues defining serviceability:

- Durability,
- Inspectability,
- Maintainability, and
- Deformations.

**Durability.** The design provisions to ensure durability "recognize the significance of deterioration of structural materials on the long-term performance of the bridge," as noted in the commentary to Article 2.5.2.1.1 of the *AASHTO LRFD Bridge Design Specifications* (1998). FRP composite scientists have conducted extensive accelerated laboratory durability tests on FRP composites, anticipating the potential exposures of the highway bridge environment. For the most part, the tests demonstrate adequate durability. However, the only true test is that of an in-service highway bridge.

FRP composites deteriorate with environmental exposure and repeated application of load. This degrading of Young's Modulus of Elasticity, $E$, has been measured experimentally in accelerated durability tests for various FRPs. If the degradation of $E$ is reliably quantified, it can be treated as losses of prestress are currently treated in the design of prestressed concrete girders. FRP composite components can be designed using the degraded $E$ estimated for the end of the design life.

**Inspectability.** There are two concerns with regard to inspectability, one technical and the other cultural. First, damage to the bridge and its components must be somehow evident for an inspector to see it. Second, in some states, inspectors on inspection teams have little formal engineering education, and, although lead inspectors are often engineers, most are not up to date on new technologies such as FRP.

Deterioration of traditional bridges is visible. Steel members corrode and lose cross-sectional area. Concrete members exhibit cracking and spalling as internal steel reinforcement corrodes and expands because of exposure to waterborne de-icing agents. Unfortunately, the deterioration of FRP (e.g., the degradation of glass fibers because of infiltration of water into the resin matrix) is not visible. Finally, proven nondestructive test methods for FRP applications have not been developed.

**Maintainability.** As cited in Article 2.5.2.3 of the *AASHTO LRFD Bridge Design Specifications* (1998), "structural systems whose maintenance is expected to be difficult should be avoided." Bridge maintenance is very different in complexity and frequency from maintenance of FRP composite materials in other applications (e.g., aerospace applications). The extent of long-term maintenance required for FRP composite materials must be demonstrated.

**Deformations.** Because of cost considerations, the most widely applied FRP composite material today is GFRP. It exhibits a relatively low modulus of elasticity, and thus most applications are governed by deflection. The optional live-load deflection criteria of Article 2.5.2.6.2 of the *AASHTO LRFD Bridge Design Specifications* (1998) are longstanding and desirable, yet rather arbitrary. For economical and thus widespread application of GFRP composites, rational live-load deflection criteria are needed. Even traditional materials are more often being governed by live-load deflection criteria, notably HPS. Obviously, FRP composite materials can meet the existing live-load deflection criteria, but better economy could be achieved if the criteria could be liberalized.

*Constructability*

Article 2.5.3 of the *AASHTO LRFD Bridge Design Specifications* (1998) indicates that "bridges should be designed . . . such that fabrication and erection can be performed without undue difficulty or distress and that lock-in construction force effects are within tolerable limits." Because of their inherently light weight, FRP composite components should be very easily erected. Fabrication to account for camber, sweep, and grade is not so easily accommodated in some FRP fabrication methods, but it is not impossible. Finally, because of the thermal reaction of FRP production, the potential for significant residual stresses exists and must be controlled.

*Economy*

Design for economy is not easily achieved with FRP composites. Without industry or government subsidy, it is questionable whether any FRP composite bridge projects would exist. No FRP composite material bridges have been constructed nor have any seismic column wraps been performed as the result of a competitive bidding process. Today, FRP composite materials are more costly than steel and concrete. Components fabricated from FRP composites are more costly than those fabricated from steel and concrete. If FRP composites are more widely used in the highway infrastructure in the near term, perhaps in the future, FRP composite materials and/or components will be less costly.

Fortunately for the future use of FRP composites in the highway infrastructure, the cost of the FRP composite material components is usually only part of the total cost of a project. The high initial costs of components can be offset by the following:

- Speed or ease of erection,
- Enhanced durability,
- Light weight and low mass, and
- Lower life-cycle costs.

If FRP composite components can be shown to have these characteristics, it will help to make a case for the use of FRP composites in certain applications. Given the current costs of FRP composites, it is clear that proponents of FRP who originally envisioned new bridge construction with FRP composites replacing a significant number of existing steel and concrete bridges were overly optimistic.

*Aesthetics*

Building aesthetically pleasing short- and medium-span highway bridges is a challenge. Designing cost-effective and physically attractive bridges with FRP composite materials will be no less of a challenge. For successful widespread application of FRP composite materials in the highway infrastructure, the design objectives outlined in the *AASHTO LRFD Bridge Design Specifications* (1998) and briefly discussed above must be met.

### Standardizing FRP Composite Materials

Bridge designers will not become material scientists just to be able to design FRP composite bridges. For successful widespread implementation of FRP composites in the highway infrastructure, the specification of FRP must be as easy as the specification of steel or concrete. Moreover, a major concern for bridge owners is being relatively certain that a product that they have specified is actually what is being used in bridge construction. With FRPs, this can be more of a challenge than it is with steel and concrete. Ensuring that the material specified is the one with which the bridge is being built is already a challenge with materials such as some new noncorroding reinforcing bars that look exactly like "black" steel. Owner acceptance tests of such rebar, which can prove the rebar's corrosion-resistance characteristics before it is installed, are important to the bridge community.

Intelligent choices should be made by materials scientists and AASHTO, narrowing the options for bridge designers. Generic material specifications, which many suppliers can meet, are needed. Proprietary materials or confusing specifications that are meant to differentiate similar products are not acceptable to the bridge community for publicly funded bridge construction.

### Use of FRP Composites in the Highway Infrastructure

FRP composites should be used intelligently. With the removal of certain obstacles to implementation, discussed below, FRP composite materials have a place in the highway infrastructure. It is unlikely that entire bridge structures, decks, superstructures, foundations, and so forth will be constructed of FRP composites. FRP composite materials will have a shared role with traditional materials in the near term and probably well into the future.

Using FRP composites in bridges may provide a potentially cost-effective alternative to all of the superstructure options available through the bridge design provisions of the *AASHTO LRFD Bridge Design Specifications* (1998), including steel, concrete, aluminum, and wood. If the marketplace is allowed to speak, FRP composite materials may go the way of aluminum, with no current usage because of prohibitive costs.

### Highway Appurtenance Design Objectives

Although bridge applications seem most promising for FRP composites, there are applications that do not have the same design practices and philosophies. For example, many highway roadside appurtenances are specified on the basis of performance characteristics rather than designed on a case-by-case basis. These items are purchased as units (usually modular), and they require installation (but not necessarily construction). Crash cushions are a typical example.

The objectives for appurtenance design are often the achievement of light weight, modularity, low cost, and maintainability. FRP composites may prove promising in this regard because they remove the need for full engineer understanding of the material-structure behavior. An appurtenance that may have design requirements met by FRP is the traffic signal. The heavy weight of traffic signals can cause problems on cantilevered mast-arm supports. Unfortunately, lighter weight traffic signals may also be more subject to wind loads blowing them off-vertical (making them harder for the roadway user to see).

## BARRIERS TO WIDESPREAD UNDERSTANDING AND IMPLEMENTATION

For the most part, the barriers to widespread implementation of FRP composite materials in the highway infrastructure are cultural, not technical (although technical barriers do exist and are included herein). These cultural barriers to successful and widespread implementation are as follows:

- Practicing bridge engineers' lack of knowledge of FRP composite materials,
- Cost,
- Lack of a simple bridge-specific material specification,
- Lack of prescriptive bridge design provisions,
- Lack of easy and reliable inspection and repair procedures, and
- Lack of encouragement from government agencies.

Technical issues include the need for reliable quantification of long-term degradation from environmental exposure and repetitive load application and the development of a design methodology that accounts for FRP composites' potential for non-ductile failure. These and the other technical issues discussed throughout this report must be addressed in any attempt to remove cultural barriers to implementation of FRP composites in the highway infrastructure.

### Practicing Bridge Engineers' Lack of Knowledge of FRP Composite Materials

Practicing civil engineers and even most newly graduated civil engineers typically have very little knowledge of FRP composite materials. If successful widespread application is to occur, these engineers are the ones who will apply FRP composite materials to the infrastructure.

The industry groups representing the traditional construction materials industries—AISI, NSBA, PCA, PCI, and the National Concrete Bridge Council—endeavor to teach the bridge-engineering community about new developments in the application of their materials to the highway infrastructure. These training efforts include bridge owners, practicing engineers, and college professors and students. Even the recent adoption of the *AASHTO LRFD Bridge Design Specifications* (1998) by AASHTO motivated industry groups to teach the community how to apply the new provisions to their materials. Similar efforts on the part of FRP composite material industry groups have been virtually nonexistent; yet, these industry groups pressure owners to use their products.

Practicing engineers' level of knowledge must grow dramatically for FRP composites to be successfully integrated into bridges. Perhaps a good indirect indicator of a material's readiness to be incorporated into the highway infrastructure is the availability of simple design examples for use by highway engineers. These exist for concrete, steel, and wood. To date, they do not exist for FRP. Although military and aeronautics industry specifications for FRP exist, they are not used in any significant way among the bridge engineering community because of significant cultural and technical differences (including, in some cases, issues as simple as differing jargon) among the industries.

Traditional materials have undergone continuous improvement to mitigate concerns about corrosion, durability, and other issues. For example, there are corrosion-resistant reinforcing steels that have been on the market for years (e.g., stainless steel) and others that have emerged more recently (e.g., MMFX steel). Although these improved materials can cost as much as FRP in their initial deployment, they enjoy one keen advantage: the materials are or at least seem to be familiar to designers who have been specifying traditional materials for years. For example, the differences in appearance, performance, and design between A36 steel and HP70W steel are small compared with the differences between A36 steel and FRP. Accordingly, these improved traditional materials are becoming de facto solutions for some targeted infrastructure problems.

### Cost

In the current marketplace, FRP composite materials are relatively expensive compared with steel and concrete. Although the costs vary depending on specific components and manufacturing type, a bridge deck made from FRP could cost two to four (or more) times (on a per-square-foot basis) what a bridge deck made from traditional materials (including even the newer HPS and HPC) would cost. In the near term, it is difficult to anticipate a change in the relative costs. Without government or industry subsidy, many FRP bridge components will not find their way into service. The factors affecting cost are not entirely understood, but they are likely to include economies of scale, perceived profit opportunity, and labor costs associated with a highly skilled workforce traditionally working on defense and aeronautics applications.

Because of their cost, a compelling case will have to be made for specifying FRP composite materials for bridge construction instead of steel and concrete. It may be that the offsetting economy of speedier construction and/or reduced weight can justify the use of FRP. This reason and others for using FRP are discussed in the white papers presented in Appendix D.

Eventually, durability may be a compelling reason for using FRP composite materials in bridge construction. Today it is not. Better assessment of life-cycle costs and proven in-service durability may in time demonstrate that the high cost of FRP composite materials is justified because of enhanced durability. Additionally, functional obsolescence needs to be considered. Bridges frequently become functionally obsolete approximately 50 to 60 years after construction. Is providing costly durability beyond 60 years cost-effective?

There is also a cost of entry into the highway infrastructure. The need for the FRP industry to invest large financial resources in order to compete in the highway infrastructure market creates a barrier to entry. Currently, the FRP industry does have other profitable outlets for its product, and thus capital investment is not a palatable choice.

### Lack of a Simple Bridge-Specific Material Specification

Bridge designers are not material scientists and should not be expected to be. The AASHTO materials specifications and the associated ASTM specifications are specific to bridges. They are developed by material engineers with assistance from bridge engineers.

For example, the material specifications for structural steel for bridges have become a single specification, ASTM A709. Several years ago, structural steel was specified by choosing from several potential ASTM specifications (e.g., ASTM A36, ASTM A588, ASTM A571, and so forth) with the addition of a separate specification for toughness. In other words, generic structural steel specifications applicable to building or bridge construction were supplemented with toughness requirements because of the cyclical nature of bridge loadings. More recently, this was simplified to a single specification, ASTM A709, which includes the toughness specification as a part of A709 and the various grades (e.g., Grade 36, Grade 50, Grade 70, and so forth) along with the suffix, “W,” for weathering steels. This simple single specification encompasses the structural steels most appropriate for bridge applications, including performance requirements specific to bridges. Recently, for simplicity, the new class of HPS was included in A709 as Grade HPS70W. Obviously, simplicity in material specifications is desirable from the point of view of the bridge community.

Material specifications for FRP composite materials must be developed that are specific to highway infrastructure applications. The most desirable solution would be a single specification for FRP composite materials including fibers, resin, and architecture. The specification should be generic, meaning that several manufacturers can meet the requirements for each of the components (i.e., fibers, resin, and architecture).

Simply because the materials commonly used today have followed a common path to implementation and success does not mean that alternate paths do not exist. However, to date, no other viable alternative path seems evident or on the horizon.

### Lack of Prescriptive Bridge Design Provisions

Bridge designers depend on rather prescriptive design provisions. Although the specifications allow general, more refined procedures, typically, designers apply the very prescriptive provisions for simplicity and to limit liability because of interpretation.

For example, the concrete-member bending-resistance provisions of the *AASHTO LRFD Bridge Design Specifications* (1998) take two forms. In Article 5.7.2, the assumptions on which the moment capacities of concrete sections are based are specified. These are the basic assumptions all civil engineers learn in their first course on reinforced-concrete design. In earlier drafts of the first edition of the *AASHTO LRFD Bridge Design Specifications,* these were the only provisions for bending resistance, with designers expected to develop their own resistance equations. The AASHTO Subcommittee on Bridges and Structures subsequently requested that an explicit, prescriptive equation be included in the specifications. Currently, Article 5.7.3.2.2 includes the equation for nominal bending resistance of concrete sections subjected to bending about one axis, the equation required for the vast majority of concrete bridge members.

Prescriptive bridge-component design provisions for FRP must be developed and incorporated in the *AASHTO LRFD Bridge Design Specifications* (1998) before successful widespread application of FRP composite materials in the highway infrastructure can be expected. These design provisions should provide adequate safety accounting for FRP composite material's potential for non-ductile failure because of its linear-elastic behavior to failure and its degradation from exposure to the environment and repeated loading.

### Lack of Easy and Reliable Inspection and Repair Procedures

The personnel performing bridge inspections and maintenance will not change to accommodate FRP composite materials. For existing personnel to continue inspecting and maintaining bridges, the techniques for inspecting and maintaining FRP composite material members must be similar in complexity to techniques used with traditional materials. In addition, inspection intervals shorter than the federally mandated biennial inspection period are not acceptable.

Loss of section because of corrosion indicates the degradation of steel bridge members with time. Spalling and cracking of concrete cover indicates corrosion and the volumetric growth of steel reinforcement with concrete bridge members. A comparably reliable and simple indicator must be identified for FRP composite materials. Similarly, when damage or degradation is identified, simple repair procedures must be available to maintenance personnel.

### Lack of Encouragement from Government Agencies

The government has the ability to encourage, limit, and even foreclose entry of industries into government-funded programs with procurement regulations, training, and similar items. To date, the U.S. government has provided sporadic support of FRP applications in highway construction, but has made no indication of full support in the future. Lack of a clear signal of intent or encouragement from government agencies undermines FRP suppliers' confidence in the viability of a long-term market.

## PROMISING NEAR-TERM APPLICATIONS

For an FRP application to be successful, the relatively high cost of FRP composites must be offset by some other factor. Two offsetting factors that are often mentioned are FRP's better durability, resulting in longer life, and the savings realized (because of the lighter weight of FRPs) in using FRP composite materials for retrofits. There are problems, however, with these two arguments. It is hard to prove to nonbelievers that FRP's durability will result in longer life for structures. Moreover, recently, contractors reconstructing highways after earthquakes on the West Coast and fires on the East Coast were able to decrease their construction time while using traditional materials. This raises the question of whether the more expensive, lightweight FRP composite materials are necessary to reduce construction time.

Of all of the applications of FRP composite materials to the highway infrastructure, five have been used most widely:

- Retrofit of concrete components,
- Retrofit of steel components,
- Seismic retrofit of bridge piers,
- Bridge decks for special applications, and
- Internal reinforcement for concrete.

White papers describing these applications were developed as part of this project and appear in Appendix D of this report. A brief discussion of each application follows.

### Retrofit of Concrete Components

Premature cracking of concrete components and inadequately reinforced concrete members are difficult to successfully repair. FRP composite materials represent a potentially revolutionary method to achieve these repairs. A well-prepared existing concrete surface provides a good interface for adhering FRP composites to the members. The basic question is the durability of the bonded interface with environmental exposure. The bonded reinforcement can be either prestressed or non-prestressed depending on the need. Obviously, the end details of prestressed and non-prestressed reinforcement will vary.

### Retrofit of Steel Components

Traditionally, corrosion loss of section or other damage to steel members is retrofitted through a bolted doubler-plate or coverplate for web or flange retrofit, respectively. Welded reinforcement is not typically considered because of the potential for creating fatigue initiation sites. The bolted retrofit in the field is very labor-intensive and thus costly. Adhesive-bonded FRP composite material retrofits can be accomplished much faster and more easily. Adhesive-bonded steel-plate retrofits would be a better solution than bolted plates, but the weight of the steel plates results in a more time-consuming and costly retrofit than the FRP plates. If the long-term durability of the bonded interface between existing steel and the FRP retrofit plates can be ensured, the cost of the FRP can be tolerated because of the other savings.

### Seismic Retrofit of Bridge Piers

Older reinforced-concrete bridge piers in seismic regions, designed before the adoption of the latest seismic design provisions, do not contain enough confinement reinforcement to provide adequate ductility in the event of a significant earthquake. In the west coast states of the United States and in Japan, such inadequately reinforced piers have been retrofitted with external steel reinforcement, or "jackets," around the perimeter of the piers to provide additional confinement.

FRP composite materials provide a viable alternative to steel jackets. Relatively little material is required, and the high cost of the FRP composite material can be offset by ease of installation. Laboratory tests have demonstrated the adequacy of FRP composite materials for this application. Many concrete bridge piers have been retrofitted with composite materials. However, in few of these projects, if any, has FRP been selected through a competitive bidding process with steel jacketing as an alternative.

### Bridge Decks for Special Applications

The preponderance of deteriorating concrete bridge decks and the promise of increased durability of FRP composite materials has resulted in many experimental and demonstration projects in which FRP is applied to bridge decks. These projects have produced mixed results.

FRP composite bridge decks are not a good solution for new bridge construction. In modern bridge construction, bridge decks are composite with their supporting members. Composite construction provides good economy and a robust structure. In such a composite structural system, the concrete deck provides the compression force of the bending-resistance couple of the cross section in the positive-moment region. FRP composite material bridge decks cannot adequately replace the compression force of the concrete deck because strains are too low to achieve much force. Thus, FRP bridge decks are not good for new bridge construction unless other issues govern.

A potential governing issue is reduced hydraulic equipment requirements for movable bridge spans; in this case, composite construction is not a factor because of the lack of continuity of the movable spans. If FRP spans are used, their light weight can result in a savings in equipment to move the span. The higher cost of the deck can be offset by a lower equipment cost. Similarly, there may be rare cases in which the reduced mass of an all-composite deck may be desirable (e.g., under exceptional seismic conditions). In this case, the desirable seismic characteristics of a low-mass FRP deck may offset its higher initial cost.

For the rehabilitation of load-restricted bridges without composite girders or stringers, FRP bridge decks represent a good potential replacement for existing concrete decks. The lighter dead load of the FRP deck in comparison with an existing concrete deck can provide greater live-load capacity. This trade-off could potentially result in lifting of load-restricting postings or lessening of these postings. The potential exists for both girder bridges and long-span bridges with floor systems consisting of stringers and floor beams.

### Internal Reinforcement for Concrete

The corrosion of steel reinforcement, both prestressing tendons and non-prestressed rebars, caused by the infiltration of waterborne de-icing agents, is the source of concrete bridge-deck deterioration. The primary solution today is protecting the steel reinforcement with epoxy coatings (as practiced in the United States) or bridge-deck membranes (as is done in Europe). Replacing the metallic reinforcement with FRP composite material reinforcement is a more positive solution. If significantly increased bridge-deck life results, the increased cost of the nonmetallic reinforcement, bars, cables, or grids may be justified. Several experimental and demonstration projects are in service. FRP could be used as cables within grouted cable stays, much as prestressing strand is used extensively today.

## SECTION 1 CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

FRP composite materials have characteristics that are desirable in highway applications, especially bridges. However, there are several significant, but not insurmountable, barriers to overcome before widespread implementation occurs. These barriers include a lack of familiarity with the material among practicing bridge engineers, the cost of the material, and the lack of a unified effort (especially from a widely accepted coordinating agency) to move implementation efforts forward.

Some applications of FRP are nearer to standardization than others, and this report characterizes those applications. Other applications may come on-line in the future. A draft strategic plan to overcome the noted barriers has been prepared (see Appendix C). In addition, white papers have been prepared on five specific applications developed (see Appendix D) to “kick start” and enhance the process of understanding and implementing FRP in the highway infrastructure.

## Recommendations

It is recommended that implementation of the strategic plan begin as soon as possible with the following:

- Organization of the workshop proposed in the draft strategic plan element titled “Buy-In from All Strategic Plan Participants” and
- Initiation of the cost-metrics study presented in the draft strategic plan element titled “Study of the Relative Costs of FRP Versus Traditional Materials.”

The AASHTO Highway Subcommittee on Bridges and Structures in conjunction with NCHRP can accomplish these recommendations through NCHRP Projects 20-7 or 4-27, as outlined in the draft strategic plan.

SECTION **2**

# OVERVIEW OF THE DRAFT STRATEGIC PLAN

## INTRODUCTION

The draft strategic plan details 11 elements necessary to achieving more widespread understanding of FRP composite materials and their application to the U.S. highway infrastructure. The 11 elements are as follows:

1. Buy-in from all strategic plan participants;
2. Acceptance, implementation, and revision of the strategic plan;
3. The means to oversee and manage the strategic plan;
4. A study of the relative costs of FRP versus traditional materials;
5. A database of practical infrastructure-based FRP knowledge;
6. Generic bridge-specific material specifications;
7. Generic bridge-specific design and evaluation methodologies;
8. Generic bridge-specific inspection and repair methods;
9. Training on FRP composite materials for practicing engineers;
10. Education on FRP composite materials for graduate civil engineers; and
11. Continuation of FHWA's Innovative Bridge Research and Construction (IBRC) program.

The plan is included in this report as Appendix C, and it is intended as a standalone document that can be disseminated separately from the research report to decision-makers and others. Some background information related to the plan is presented here, primarily documenting the basis for the overall strategic plan and its elements. The plan itself has information on each of the following items:

- Individual elements,
- Action items or tactics to help ensure implementation of the element,
- A schedule for the element and its associated tactics,
- Responsible parties to lead activities for each element of the overall plan, and
- Performance measures and benchmarks for the individual elements of the plan.

## BASIS FOR THE DRAFT STRATEGIC PLAN AND ITS ELEMENTS

Strategic planning begins by considering three questions:

1. Where are we today?
2. Where do we want to be tomorrow?
3. How do we get there?

Through a review of practice, literature, and a questionnaire sent to state DOTs, several things were determined. First, a baseline level of understanding and knowledge of the existing technologies, needs, and applications was determined. This provides the answer to the first question. The existing technologies, needs and applications have been discussed in Section 1 of this report.

The answer to the second question stems, in part, from the first question. Based on current applications and needs, two fundamental issues arose with regard to the strategic plan:

- Which highway applications are most likely to be successful candidates for the integration of FRP technology?
- What has to happen within the highway and FRP communities, as well as others, to successfully apply the technology to those applications?

The draft strategic plan identifies applications that represent the most likely near-future success stories for FRP. Information related to the specific need met by the use of FRP and the nature of activities related to each application are described in the white papers in Appendix D.

The third question is answered by the 11 elements of the strategic plan and the specific tactics discussed below for actualizing the plan.

Because strategic planning is part art and part science and because absolute control of the marketplace or highway community is not possible, no prescribed routine can *guarantee* a successful strategic plan. However, strategic plan elements and activities were ranked qualitatively regarding their probability of success. This probability of success was based on personal experience as well as information (both published and anecdotal) gathered during the course of the project.

The strategic plan for NCHRP Project 4-27 was developed so that it would share the characteristics of most successful strategic plans (a successful strategic plan in this case would be one that is implemented and producing the desired results). Successful strategic plans have generally been shown to share the following characteristics (Anthony, 1985):

- Recognition of the outside environment and explicit incorporation of elements of that environment into the planning process;
- A long-term focus—sometimes 3 to 5 years, but often 10 to 20 years;
- Influence and information from the top of organizations;
- Required commitments of large amounts of organizational or multi-organizational resources; and
- Identification of "where things stand" in a changing environment.

The draft strategic plan presented in this report was based in part on these characteristics. The ways in which these characteristics served as a basis for the strategic plan are described below.

**Recognition of the outside environment and explicit incorporation of elements of that environment into the planning process.** One of the major discoveries of the project was that the highway community's interest in integrating FRP into the highway infrastructure was not so much an explicit or exclusive interest in FRP as it was an interest in finding better technologies to meet at least three needs:

- The need for more durable infrastructure elements,
- The need for infrastructure elements that can be constructed more quickly, and
- The need for cost-effective construction techniques on both first-cost and life-cycle bases.

There are technologies other than FRP that meet these needs. For example, precast concrete bridge-deck panels are both durable and quickly constructed. Advanced HPS and HPC provide both durability and faster construction time and may provide better first-cost and life-cycle costs than conventional steel or concrete construction. The strategic plan developed in this project needed to reflect the needs of the highway community and the nature of competitive alternatives to FRP.

**A long-term focus—sometimes 3 to 5 years, but often 10 to 20 years.** The highway industry, as well as the construction industry as a whole, has traditionally been slow to replace older, tried-and-true technologies with new ones. When developing the draft strategic plan, the research team took care not to overemphasize activities that would perhaps have short-term success but that might not provide the sustained interest and implementation necessary to prevent FRP from being seen as a "flash-in-the-pan" technology. For example, the draft strategic plan does not include an element that might suppress FRP costs in the short term because it is probable that if costs rose in the future other technologies would again become more competitive. Short-term cost suppression, in and of itself, was not deemed desirable for a strategic plan geared toward long-term success.

The draft strategic plan focuses primarily on two time horizons. The first time horizon includes short-term, near-future activities in the first 1 to 3 years of the plan that will broaden the desire to see FRP succeed and will set the stage for the institutional changes necessary to accommodate sustained and increased use of FRP in the future. The second time horizon includes longer-term (5- to 10-year) activities that are meant to help FRP become a commonplace technology, one for which the institutional and technological knowledge base is parallel to that which exists for conventional materials such as steel and concrete.

**Influence and information from the top of organizations.** The plan is based on the input and expectations of groups that drive the selection of infrastructure technologies and the improvement of those technologies. Standing out among these groups is the AASHTO Highway Subcommittee on Bridges and Structures, whose members promulgate new technologies and whose activities and endorsements of technologies result in commonly accepted standards of practice (e.g., by the adoption of appropriate AASHTO specifications). Information was also gathered from high levels within the federal government, most notably at FHWA and the National Science Foundation (NSF). The draft strategic plan was developed with the recognition that it must reflect, at least to some degree, current efforts by these groups as well as their willingness to embrace new technologies. In addition, information was garnered from presentations by persons representing the FRP manufacturer community, such as the MDA. The MDA serves to indicate, in a clear and concise manner, the direction that FRP manufacturers are heading with respect to the use of their product in the infrastructure. The draft strategic plan was based on an understanding of past, ongoing, and planned research that is broad and national in scope, including efforts sponsored by FHWA, AASHTO (through NCHRP), and NSF.

**Required commitments of large amounts of organizational or multi-organizational resources.** The draft strategic plan includes estimates of resource needs for successful implementation. It was developed with the knowledge that dedication of the required resources cannot be controlled and that a compelling argument is needed for both public and private organizations to continue to invest in FRP or redirect their investments into this technology. The plan intentionally included some elements that are perceived as having low cost and high payoff, with the recognition that these parts of the plan might be the most readily initiated by its champions and might build support for other, more costly elements in the plan. However, the plan was not structured so that the least expensive activities come first; instead, it was conceived so that parts could move forward pending the commitment of large resources by the participants.

**Identification of "where things stand" in a changing environment.** The interim report for this project, which has been modified slightly and included as Section 1 of this final report, provided a candid evaluation of FRP technology that indicated past and current FRP activities, competitor technologies, and the perceived future of FRP and the competitor technologies. This identification helped the draft strategic plan to be developed without unrealistic expectations.

## AVOIDING FAILURE OF THE STRATEGIC PLAN

In part, the plan was developed as much on the principle of avoiding what would make it fail as it was on pursuing what would make it succeed. NCHRP Project 4-27 is not the first effort at strategic planning related to the integration of FRP into the highway infrastructure. Many groups have done planning, and many of these plans or portions thereof are excellent. However, none has become commonly accepted as *the* strategic plan for the highway community. As Project 4-27 moved forward, participants kept in mind several of the reasons that strategic plans fail and attempted to avoid or reduce activities related to such pitfalls. The reasons for failure of strategic plans have been identified in the literature (Policastro, 1992; Forbes, 1996) and are noted in Table 3 below, along with a discussion of how NCHRP

**TABLE 3 Reasons for strategic plan failures and steps taken to avoid failure**

| Reasons for Failure | Project Steps Taken to Avoid Failure |
|---|---|
| Plan lacked detailed implementation steps with tasks, schedules, and responsibilities. | • Tactics for implementing the plan elements have been developed.<br>• Schedules for each element have been provided.<br>• Lead organizations have been identified for each element. |
| Goals were not stated in quantifiable terms. | • Several (but not all) of the elements have quantifiable portions. In some cases, where quantification was difficult, indication of "increases" or "decreases" was used. |
| Key industry, government, and/or other personnel were not involved. | • The plan requires endorsement by key figures, especially in the public sector (AASHTO, FHWA, NSF). |
| Funding/resource levels required were not identified, or there was not a reasonable expectation that commitments for needed resources would be made. | • The funding/resource levels are modest for some elements so that constrained funding availability should not be cause for not pursuing the element.<br>• Where practical, funding/resource requirements are identified (albeit in some cases as gross estimates). |
| Plan focused exclusively on technology and/or finance and neglected policy considerations. | • One of the major elements of the plan is related to policy—the development/endorsement of an umbrella group to help guide FRP activities. |
| Plan failed to perceive the barriers to entry. | • Issues related to barriers to FRP were investigated and discussed in the interim report.<br>• Plan elements were not included unless methods to overcome barriers to entry existed. |
| Plan was developed through unstructured discussion over a very short period of time. | • The plan was developed based on intense consideration over a long period of time, and with public discussion of portions to weed out extemporaneous and inappropriate elements. |
| Plan was not documented for evaluation/consideration by others in the future. | • The development of the plan is being documented in the deliverables of the project (proposal, interim report, draft strategic plan, preliminary draft final report, and revised final report). Several of these pieces will be readily available for widespread review. |
| Strategic-planning efforts from others in the past were not identified and used. | • The plan has been based on information garnered from NSF about past FRP strategic-planning efforts and masonry-planning efforts. Past FHWA work has also been considered, as has NCHRP strategic-planning efforts related to scour of bridges. |
| Too few people were held responsible for the success or failure of the plan. If too few people are held accountable for the plan's outcome, it has little chance of success. | • The plan includes roles for specific organizations so that accountability and attribution are possible. However, at the same time, effort is spread among enough parties to make each constituent's role executable. |
| No one is rewarded or sanctioned as a result of the success or failure of the strategic plan. | • This is perhaps the most difficult issue for the plan development; the plan relies in large part on professional reputation as the reward or sanction associated with how the plan fares. |

Project 4-27 attempted to avoid introducing plan elements that might fail.

It is worth noting that, in some cases, elements of the draft strategic plan are purposely left less specific than they otherwise might be. For example, a few elements of the draft strategic plan deal with proposed research efforts by NCHRP or FHWA. Although activities and guidance that are considered important to those projects have been described, detailed project statements have not been drafted. This is because of the fast-changing nature of the FRP industry, the highway industry's use of the material, and the desirability for groups (in NCHRP's case, project panels) with specific expertise to develop statements that are the most appropriate and focused on the research needs as perceived at the time of project initiation.

## ADDRESSING BARRIERS TO ENTRY

One of the major issues that must be overcome for the successful integration of FRP technology in the highway infrastructure is that of barriers to entry. Typically, the barriers discussed below exist for products and technologies trying to enter an industry. Following each listed barrier is a discussion of how the barrier was considered or handled during development of the strategic plan.

***Economies of Scale.*** *Economies of scale deter entry by forcing a technology to enter an industry at a large scale and risk strong reaction from existing technologies or enter at a small scale and accept a cost disadvantage. Both are undesirable options.*

The draft strategic plan includes some elements that allow for targeted introduction or improvement of FRP technology in areas in which the benefits of FRP compared with other approaches are clear and generally accepted. In this way, the plan does not require FRP to become, either immediately or in the short term, a total competitor to conventional construction materials. However, these targeted applications (noted in the white papers in Appendix D) represent a significant enough market for FRP products as to allow the industry to realize a meaningful return on its investment and to provide a significant enough number of applications so that the understanding and use of FRP technology can spread to other applications. Moreover, the plan explicitly considers the issue of cost, noting that an appropriate cost-metrics study is required before full-blown attempts to enter the market are endorsed by the highway and/or FRP communities. It is worth noting that the plan does not suggest elements or tactics that would artificially and temporarily lower the cost of FRP technologies; this was seen as a maneuver that might result in long-term concern and distrust if and when costs returned to market-based levels.

***Product Differentiation.*** *Differentiation creates a barrier to entry by forcing entrant technologies to spend heavily to overcome existing customer loyalties to and understanding of existing technologies.*

The draft strategic plan is based on the belief that FRP must be treated as much as possible as *simply another construction material.* The plan provides short-term and long-term strategies to meet this goal. These strategies include supporting additional deployments of the technology to demonstrate its usefulness, durability, and ability to meet multiple design requirements, as well as supporting upstream integration of FRP knowledge into college curricula to mitigate the current tendency among practicing structural engineers to see FRP as a novelty. This latter point is analogous to successes seen with other construction technologies. For example, TMS and NCMA spearhead efforts to introduce professors and students to masonry technology so that it can be perceived as "just another tool in the toolbox" when students graduate and become practitioners.

***Capital Requirements.*** *The need for the FRP industry to invest substantial financial resources in order to compete creates a barrier to entry.*

The draft strategic plan allows for targeted investments by the FRP industry, investments that may be scaled up as time progresses. Moreover, the plan calls for actions that should be clear signals from the highway community regarding its seriousness about using FRP in the future; this should help to reduce the risk that the FRP industry may perceive as it prepares to invest additional resources.

***Switching Costs.*** *A barrier to entry is created by the costs facing the buyer who is switching from one technology to another or who is accommodating both existing technologies and new ones.*

Efforts have been made to treat FRP as similarly as is practical to other materials in order to reduce switching costs. In addition, by focusing on the targeted applications shown in the white papers, the draft strategic plan focuses on applications for which FRP may be readily considered the best alternative, thus reducing perceived switching costs.

***Disadvantages Independent of Scale.*** *Established technologies may have cost advantages not replicable by potential entrants. The most critical factors include the following:*

- Proprietary product technology and
- Learning or experience curve.

Perhaps the most difficult issue associated with FRP technology is to alter the proprietary product mindset of manufacturers and users. The elements in the plan are intended to make it desirable and obvious to FRP manufacturers that achieving at least some commonality with the methods used for steel and concrete construction, such as generic, non-product-specific specifications, will result in a higher likelihood of increased market share. On the owner side, the plan has been drafted to be open to performance-based specification development, and the plan employs mechanisms that it is hoped will reward innovation in this way.

The plan was developed to explicitly deal with the issue of learning and experience. This is true both for current practitioners and for those in undergraduate engineering education.

***Government Policy.*** *The government can encourage, limit, and even foreclose entry industries with procurement regulations, training, and similar items.*

One purpose of the draft strategic plan is to send a stronger message than before that the highway community is serious about wanting to use FRP. The plan was developed to encourage explicit, public actions by government agencies to demonstrate the seriousness and duration of policies to assist in implementing FRP technology and expanding its application.

***Pressure from Substitute Technologies/Products.*** *Substitutes limit the potential returns of an industry by placing a ceiling on the price that firms in the industry can charge. The more attractive the price-performance alternative offered by substitutes (such as steel, wood, and concrete), the firmer the lid on industry profits.*

The draft strategic plan was developed to accentuate activities and applications for which conventional materials are notably lacking in their ability to meet design requirements or desires. This emphasizes some of the disadvantages of substituting materials only because of cost. The plan does not encourage head-to-head competition between FRP and conventional materials for many current bridge applications, specifically because of cost, information, and technology limitations.

## SECTION 2 CONCLUSION

NCHRP Project 4-27 has investigated the ongoing and potential integration of FRP technology into the highway infrastructure, including a review of literature, a study of practice, and a determination of technical and cultural issues associated with the long-term successful application of FRP in the highway infrastructure. The following was developed or noted:

- A draft strategic plan (see Appendix C) was developed to enhance the understanding and eventual deployment of FRP technology in the highway infrastructure. The plan addresses cultural, organizational, technical, and economic issues. The elements of the plan are essential for the long-term success of FRP.
- White papers (see Appendix D) were drafted for five applications of FRP deemed to have the most potential for success. These papers detail the relevant issues of design, cost, training, and other considerations.

The implementation of the research results for this project requires simply that the ideas and tactics noted in the strategic plan be carried out.

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# GLOSSARY OF ACRONYMS

ACI: American Concrete Institute
AISI: American Iron and Steel Institute
CFRP: carbon fiber reinforced polymer
DOT: department of transportation
FRP: fiber reinforced polymer
FY: Fiscal Year
GFRP: glass fiber reinforced polymer
HPC: high-performance concrete
HPS: high-performance steel
IBRC: Innovative Bridge Research and Construction
LRFD: load and resistance factor design
MDA: Market Development Alliance of the FRP Composites Industry
NCMA: National Concrete Masonry Association
NSBA: National Steel Bridge Alliance
NSF: National Science Foundation
PCA: Portland Cement Association
PCI: Precast/Prestressed Concrete Institute
PRS: performance-related specification
QA/QC: quality assurance/quality control
TMS: The Masonry Society
VMS: variable message sign

# APPENDIXES A AND B

## UNPUBLISHED MATERIAL

Appendixes A and B as submitted by the research agency are not published herein. For a limited time, they are available for loan on request to NCHRP. Their titles are as follows:

Appendix A: Questionnaire
Appendix B: Summary of Responses to Questionnaire

# APPENDIX C

# DRAFT STRATEGIC PLAN

## INTRODUCTION

The highway infrastructure has problems that have not been solved by the continuing and improving use of conventional materials such as steel and concrete. Steel bridges continue to corrode despite painting and other protective actions. Concrete bridge decks and beams spall when the internal rebar rusts from the sodium chloride of winter maintenance activities or from exposure to marine environments. Repairs continue to take a long time, and traffic volumes demand shorter construction periods. Heavier loads are crossing bridges that were designed for lighter ones, and budget limitations prevent wholesale strength upgrading of the infrastructure. These issues will continue to grow with time.

The search for solutions has been going on for some time. The solutions include better maintenance strategies, enhancements to traditional materials, and, more recently, investigation and implementation of fiber reinforced polymer (FRP) materials, which were developed primarily for the defense and aerospace industries. These materials are light weight, strong, and durable, and they have the potential to address many highway infrastructure problems.

FRP is basically a composite of strong, stiff fibers bound together by a resin matrix. The fibers can be made from glass, carbon, and other materials. The material components, the manufacturing process, and the inherent engineering allow FRP to be made in many different ways and to exhibit many different performance characteristics. It is therefore unlike a single bridge steel, which is very similar from bridge to bridge and from manufacturer to manufacturer.

Anticipating the promise of FRP, FHWA set up a program to encourage experimental use of FRP in highway structures, and some 150 demonstration applications have been conducted to date. Results have been both promising and disappointing, with some knowledgeable people believing that the highway community is ready for wider deployment of FRP, whereas others are less sure, seeking either additional information about deployment or better information on the long-term efficacy of pursuing FRP as a significant component in highway construction or repair.

The AASHTO Highway Subcommittee on Bridges and Structures, as well as others desiring to accelerate the harvesting of benefits from FRP technology, proposed the development of a strategic plan to assist the deployment of FRP. This draft strategic plan is the result of NCHRP Project 4-27, which was funded to address these issues. The goal of the plan is to increase understanding of FRP among the highway and FRP communities and promote deployment of FRP materials.

NCHRP Project 4-27 examined the literature on FRP and technology demonstrations and potential applications for FRP. This project also looked at the culture and practices of the potential customers of FRP (e.g., state departments of transportation [DOTs], turnpike authorities, and design consultants) and the producers and manufacturers of FRP. The following conclusions were drawn:

- There are some candidate applications for FRP (e.g., bridge strengthening and repairs) for which knowledge is nearly adequate and benefits are great; for these applications, FRP is ready for widespread deployment. However, candidate applications are limited.
- FRP has potential in many other applications, but much more work is required to achieve and demonstrate those benefits.
- The highway and FRP communities can advance the harvesting of this potential by implementing a strategic action plan with an emphasis on accelerating *understanding* of the technology rather than an exclusive emphasis on accelerating the *deployment* of FRP.

## STRATEGIC PLAN ELEMENTS

This draft strategic plan consists of 11 elements necessary to achieving more widespread understanding of FRP materials and application of these materials to the U.S. highway infrastructure. These 11 elements are the following:

1. Buy-in from all strategic plan participants;
2. Acceptance, implementation, and revision of the strategic plan;
3. The means to oversee and manage the strategic plan;
4. A study of the relative costs of FRP versus traditional materials;
5. A database of practical infrastructure-based FRP knowledge;
6. Generic bridge-specific material specifications;
7. Generic bridge-specific design and evaluation methodologies;
8. Generic bridge-specific inspection and repair methods;
9. Training on FRP composite materials for practicing engineers;
10. Education on FRP composite materials for graduate civil engineers; and
11. Continuation of FHWA's Innovative Bridge Research and Construction (IBRC) program.

The discussion of each element of the draft strategic plan is organized into the following topics:

- Background and description of the element;
- Lead participants from the highway community;
- Specific tactics (action items) to implement the element;
- An approximate schedule for initiation and completion (shown in months, with the starting time being completion of NCHRP Project 4-27 or endorsement of the overall draft strategic plan by AASHTO);
- Resource requirement estimates (e.g., time, funding, and other resources) to implement the element; and
- Performance measures for the element (including benchmarks, when appropriate).

Several of the elements require some "seed money" to get the process started. Various avenues of funding exist. Perhaps the most direct approach would be for the state DOTs to use their State Planning and Research (SPR) funds. Interested states could initiate a pooled-fund study that would get time-critical aspects of several elements of the strategic plan going. (In other words, the study might not address all of the content of any single strategic plan element, but would instead get several of the elements started.) A requirement for some level of matching funds from private industry could help to both enhance the size of the seed money pot and ensure industry involvement in the process. Appropriate methods for ensuring industry input and governance in the process would be required.

Further, although the academic sector is probably least able to provide seed money in the form of cash, in-kind support can certainly be provided through the donation of time by interested research and teaching faculty. If enough seed money can be generated to undertake a workshop and initiate an umbrella group, then brainstorming by those two entities might enable additional fast-track monies to be identified.

Table C-1 presents a summary of the draft strategic plan.

**TABLE C-1 Summary of draft strategic plan**

| WHAT IS NEEDED | WHY | WHO | HOW | WHEN |
|---|---|---|---|---|
| Workshop of funding agencies, researchers, owners, designers, and FRP producers | Much confusion exists among practicing engineers about FRP composite materials and among researchers and FRP producers about bridge engineering. Foster a buy-in from all needed parties. | National Cooperative Highway Research Program (NCHRP) | 3-day workshop on refining and implementing the strategic plan. | 1st |
| Steering Committee to review progress and provide redirection | As the strategic plan is implemented, some portions of the effort may be delayed or go undone, and redirection of the effort may be needed. | NCHRP | At the conclusion of the 3-day workshop establish a strategic-plan steering committee representing funding agencies, researchers, owners, designers, and FRP producers, and host regular meetings. | 1st |
| Development of cost metrics | No comprehensive study to establish the cost-effectiveness of FRP composite materials has been conducted. | NCHRP | Develop and fund an NCHRP project to study the cost-effectiveness of FRP composites. | 1st |
| Collective database of practical infrastructure-based FRP knowledge. | Much experience is being generated by the Innovative Bridge Research and Construction (IBRC) program demonstration projects, yet little collective knowledge is being created. | Federal Highway Administration (FHWA) | Develop and fund an FHWA project to compile and synthesize IBRC experience to date. | 1st |

(*continued on next page*)

**TABLE C-1 (Continued)**

| WHAT IS NEEDED | WHY | WHO | HOW | WHEN |
|---|---|---|---|---|
| Generic bridge-specific material specifications | Generic bridge-specific material specifications do not exist. | National Science Foundation (NSF) and/or FHWA (with help from FRP producers) | Develop and fund an NSF and/or FHWA project to develop generic bridge-specific material specifications. | 2nd |
| Generic bridge-specific design and evaluation methodologies and provisions | Generic bridge-specific design and evaluation methodologies and provisions do not exist. | NSF and/or FHWA (and/or NCHRP) | Develop and fund NSF and/or FHWA (and/or NCHRP) projects to develop generic bridge-specific design and evaluation methodologies and provisions. | 2nd |
| Generic bridge-specific repair and inspection methods | Generic bridge-specific repair and inspection methods do not exist. | NCHRP | Develop and fund an NCHRP project to develop generic bridge-specific repair and inspection methods. | 2nd |
| Trained practicing engineers (owners, designers, and inspectors) | Practicing engineers experienced in the construction, design, inspection, evaluation, and maintenance of steel, concrete, and wood bridges have little or no experience with FRP composite material bridges. | National Highway Institute (NHI) | NHI training course offered to DOTs and others. | 3rd |
| Educated graduate engineers | Civil engineering undergraduate programs do not typically include FRP composite materials as a significant part of the curriculum. | NSF<br>U. S. Dept. of Education | Curriculum development programs and strategies to incorporate civil-engineering-specific FRP composite material and structural-design courses into Civil Engineering curricula. | 3rd |
| Continuation of IBRC program | The IBRC program provides a continuously growing database of practical experience. | FHWA | Continue the program | 3rd |

**Buy-In from All Strategic Plan Participants**

*Background/description:* To achieve buy-in from the various participants, a 2½-day strategic plan workshop is proposed. The invitees to the workshop will be research- and demonstration-project funding agencies, researchers, infrastructure owners, designers, and FRP producers and fabricators. (Producers make the raw materials, fibers, and resins. Fabricators make components from the raw materials.) The goals of the workshop will be to

- Introduce the draft strategic plan to all necessary parties,
- Potentially refine the plan based on the views of the parties, and
- Achieve buy-in from all participants through fostering joint ownership of the plan.

At the point of acceptance of the plan by the participants, it should no longer be considered a "draft" strategic plan. In addition, when the final plan has been agreed to, it should be disseminated widely. Buy-in entails not only the joint ownership of the plan by all participants but also public statements of support for the plan by participants, and, more importantly, support of the plan goals through funding and in-kind support.

*Lead participants:* The workshop could be funded by NCHRP on behalf of the AASHTO Highway Subcommittee on Bridges and Structures' Technical Committee on Fiber Reinforced Polymer Materials (T-6).

*Tactics:* Either of the following routes could be followed to obtain funding for the workshop:

- The AASHTO Highway Subcommittee on Bridges and Structures, perhaps in conjunction with other subcommittees (e.g., Materials, Design, Construction, and Maintenance), could request an NCHRP Project 20-7 Task Study to conduct the workshop.
- The NCHRP project panel overseeing Project 4-27 could request the use of NCHRP implementation funds (NCHRP Project 20-44) for the workshop.

In either case, the workshop should involve the following:

- It should be coordinated by consultants familiar with both the highway community and the FRP industry. It is essential that the workshop be co-organized and conducted by a well-known and respected member of the highway community and by a member of the FRP industry with equivalent stature. This will help to ensure that there is no undue bias toward either the application market or the goods/services providers, and it will also help to develop a sense of trust and cooperation.
- The invitees to the workshop should include highway infrastructure designers, constructors, and maintainers; FRP suppliers and fabricators; and researchers who work in the realm of highway infrastructure design and construction. It would be strongly desirable to have organizations that represent these constituencies present, including the various professional societies that are affiliated with highway innovations and advanced materials. The suggested number of participants is 25, a number that provides for workable discussions while also allowing for subgroups to focus on specific elements of the plan for detailed review.
- The draft strategic plan should be provided to workshop participants in advance so that constituents can perform an advance review as well as obtain feedback and opinions from colleagues, agency constituents, and others.
- It should begin with a day of introductory material and introductions, and an overview of the workshop scope should be presented. This would be followed by approximately 1½ days of in-depth discussion on each element. Finally, ½ day would be set aside for consensus building on the final strategic plan and the resolution noted below.
- It should conclude with a nonbinding resolution, agreed to by all workshop attendees, endorsing the strategic plan (with any modifications that may have arisen during workshop deliberations).
- A pamphlet highlighting the final strategic plan content should be prepared and widely distributed to the highway and FRP communities. It is recommended that a format similar to that used for disseminating the results of *NCHRP Synthesis 280: Seven Keys to Building a Robust Research Program* be employed. For *NCHRP Synthesis 280,* an 8.5-inch by 11-inch tri-fold glossy pamphlet was used to concisely and effectively communicate research results to executives and research managers.

*Schedule:* The request for funding of the workshop should begin immediately. The workshop should be conducted no more than 4 months after funding is appropriated. This schedule allows approximately 1 month for bringing consultants on board to organize and facilitate the workshop, 1 month for settling workshop logistics (e.g., date, location, and participants), and 2 months of lead time for participants to review material and prepare for the workshop. Care must be taken to schedule the workshop for dates that are convenient for both the highway and FRP communities as a whole.

*Resource requirements:* The workshop can be conducted for $60,000, which includes a travel/lodging allocation of up to $1,000 per participant, funding for the facilitators, rental of workshop space, and workshop events (e.g., meals, breaks, and so forth).

*Performance measures:* The following measures will indicate the success of this element:

- Initiation and conduct of the workshop in the prescribed time frame.
- Successful passage of a resolution endorsing the (perhaps modified) draft strategic plan.
- Dissemination of the results to the technical community through articles within the communications lines of organizations ("internal communications") and to the community at large through articles in widely read organizational publications.
- Buy-in to the plan indicated through the plan's incorporation into AASHTO's and FHWA's individual strategic plans for their agencies.
- Buy-in to the plan by all participants, with joint ownership represented by public statements of support and by funding and in-kind support of the goals.

These measures are, by their nature, binary: either they will have been done or they will not have been done.

**Acceptance, Implementation, and Revision of the Strategic Plan**

*Background/description:* To date, no clear “go-to” group for FRP integration into the highway infrastructure has emerged. The AASHTO Highway Subcommittee on Bridges and Structures (through the Technical Committee on Fiber Reinforced Polymer Materials [T-6]) and the Subcommittee on Materials have been strongly involved with design and material specification development, as well as with trial applications of technologies. The Market Development Alliance of the FRP Composites Industry (MDA) has become an information source and proponent of the use of FRP. The National Science Foundation (NSF), FHWA, and NCHRP have all been major participants in outlining, funding, and directing FRP-related research. However, no umbrella group has emerged with which each constituency freely and regularly interacts as equal or near-equal partners. The AASHTO groups have, as is their charge, membership restricted to state and FHWA employees. Manufacturer groups are guided primarily by private-sector membership. What is needed is an umbrella group that does not necessarily exert authority over other groups but is seen as an unbiased home for the open discussion of FRP needs and activities.

It is perceived that this group may serve a function similar to that served by The Masonry Society (TMS) in the building construction world. TMS serves as an umbrella organization for individual members (e.g., structural designers and architects), single-business members (e.g., an individual masonry manufacturer), and industry groups (e.g., the National Concrete Masonry Association and the Brick Industry Association). TMS helps to facilitate educational, research, and implementation activities for masonry construction in general, despite the often competing interests of the clay and concrete masonry industries or of one manufacturer and another. The umbrella group should be similar to groups in the bridge community like the American Iron and Steel Institute (AISI), the National Steel Bridge Alliance (NSBA), or the National Concrete Bridge Council. For example, the AISI and NSBA co-sponsor semi-annual meetings of AASHTO Technical Committee T-14 to update and maintain the AASHTO steel specifications.

A critical characteristic of a successful umbrella organization is for it to represent owners, designers, suppliers, and fabricators in an even-handed and cooperative manner. This group would become responsible for the long-term handling of strategic plan elements (e.g., measuring performance, making revisions, and so forth). The research team cannot designate an umbrella group. Hopefully, a suitable group will either become or organize the umbrella group. This umbrella group is pivotal to the entire strategic plan, yet the participants in this research project cannot force any existing entity into this role.

*Lead participants:* Groups that undoubtedly should seek representation on the umbrella group include AASHTO, FHWA, NSF, the U.S. Department of Defense (DOD), MDA, the Society for the Advancement of Material and Process Engineering, the American Consulting Engineers Council (ACEC), the American Road and Transportation Builders Association (ARTBA), and ASCE. It seems appropriate that the workshop discussions should include an action plan for both developing the membership of the umbrella group and constructing a business plan for it.

*Tactics:* It is essential that the resolution from the workshop (see “Buy-in from All Strategic Plan Participants”) include an agreement on the need for this umbrella group; this will provide the impetus and sanctioning from participating bodies that is necessary to give the umbrella group stature and perceived authority. It is further recommended that articles related to this effort to develop an umbrella group be published by major periodicals that are read by large percentages of the highway and FRP communities. Such periodicals include the following:

- ASCE’s *Civil Engineering,*
- ASME’s *Mechanical Engineering,*
- *Structure,*
- TRB’s *TRNews,*
- *The AASHTO Journal,*
- ARTBA’s *Transportation Builder,*
- *Engineering News-Record,* and
- *Structural Engineer.*

Seed money for the umbrella group will be necessary, and it may be desirable for groups to provide seed money to support the umbrella group’s initial year or so of operation. A similar tack was used by the Highway Innovation Technology Evaluation Center (HITEC), which obtained some funding from FHWA and others. Eventually, the umbrella group should be weaned from such support and become self-sufficient. Semi-annually, this group should also report on the status of the strategic plan implementation on the needs identified in the strategic element, “The Means to Oversee and Manage the Strategic Plan.”

*Schedule:* Forming the umbrella group cannot effectively begin until the workshop has been conducted and its elements endorsed. However, potential sponsors/participants in the umbrella group should be participants in the workshop; therefore, the groundwork will be laid as part of the workshop activities. Accordingly, it is proposed that specific activities related to the umbrella group be initiated at the conclusion of the workshop, with the development of funding and putting a business plan and structure in place occurring during months 5–12 following NCHRP Project 4-27. The umbrella group is expected to last indefinitely.

*Resource requirements:* The umbrella group will require some staffing (which could start out as one clerical/administrative staff member, one technical staff member, and one executive staff member), a widespread marketing and communication effort, significant funding for travel, and a business space that is independent of any of the single constituencies that look to the umbrella group for leadership. However, it is suggested that the umbrella group might operate in much the same way as the Strategic Highway Research Program, using staff "on loan" from state transportation and other agencies. This may be difficult with respect to obtaining state DOT representation, except perhaps for larger states with larger staffs. The benefit of using an "on-loan" approach is that the staff will be composed of persons with recognized names and expertise. An estimated first-year budget of $750,000 should suffice. This first-year budget may seem large and thus difficult to solicit; however, in comparison with the profit to be made by the private sector and the costs to be saved by the public sector if FRP composite materials prove their potential, the dollar amounts required for the strategic plan are small. The potential value of FRP must be demonstrated to those solicited for the funds. In-kind support may replace a portion of these amounts also.

*Performance measures:* Implementation of this strategic plan element can be measured using the following metrics:

- Has the concept been endorsed as part of the strategic plan workshop?
- Has the umbrella group been implemented as a business unit (measured in terms of actual dedicated operating budget and staff at first)?
- What is the extent of awareness and acceptance of the leadership role of the umbrella group (indicated by user familiarity and acceptance of the group, which can be measured through an appropriate survey of the constituencies looking to the umbrella group for leadership)?
- Have sponsors of highway infrastructure research encouraged new FRP projects through their solicitations or awards (e.g., in the NCHRP IDEA program or the Civil Engineering Research Foundation's HITEC program)?

The following benchmarks are offered as measures of the success of this element:

- Start of group: 0–5 percent recognition of group name or its mission, 0–5 percent faith or trust in its leadership position and activities. (The percentages of recognition are out of the population of decision-makers in the bridge-construction industry. This includes decision-makers among owners, consulting engineers, contractors, and suppliers. If deemed appropriate by the umbrella group, a simple, well-distributed questionnaire may quantify these benchmarks.)
- After 1 year of operation: 20 percent recognition of the group name or its mission, 10 percent (of those recognizing) having faith or trust in its leadership position and activities.
- After 2 years of operation: 35 percent recognition of the group name or its mission, 25 percent (of those recognizing) having faith or trust in its leadership position and activities.
- Year 3 and continuing: 50 percent recognition of the group name or its mission, 50 percent (of those recognizing) having faith or trust in its leadership position and activities.

In addition, performance measures to ensure an adequate level of activity (although not necessarily the impact of that activity) should be included. The following will serve as measures of activity.

- During Year 1:
  - At least one presentation to each major constituency,
  - At least two major informational publications (published by the umbrella group itself) that are widely circulated, and
  - At least three articles published in relevant constituent-based publications.
- During Year 2:
  - At least one presentation to each major constituency,
  - At least two major informational publications (published by the umbrella group itself) that are widely circulated,
  - A quarterly newsletter that is widely circulated, and
  - At least three articles published in relevant constituent-based publications.
- Year 3 and beyond: To be determined.

**The Means to Oversee and Manage the Strategic Plan**

*Background/description:* For the strategic plan to succeed, it must be reviewed and potentially redirected or otherwise managed if the required results are not achieved. A steering committee could be appointed to review the progress of the strategic plan implementation and provide any required redirection. Although this activity is almost a subset of the activities that the previously mentioned umbrella group would undertake, it is essential that a specific committee responsible solely for strategic plan monitoring and enactment be set up; in this way, the umbrella group can focus on executing actions, marketing strategies, and so forth, while the steering committee can look more at the big picture and also determine how strategic plan implementation is progressing.

*Lead participants:* The membership of the strategic plan steering committee could be similar to that of Technical Activities Division committees at TRB (with members from state DOTs, federal agencies, the private sector, and academia), in other words, similar to the make-up of the constituencies of the umbrella group. Strong representation should come from the Technical Committee for Fiber Reinforced Composites (T-6) of the AASHTO Subcommittee on Bridges and Structures because of the promising early applications of FRP related to bridges, this committee's momentum related to FRP efforts, and their regular meetings (the steering committee meetings could coincide with Technical Committee T-6 meetings, although this may not be feasible). Technical Committee T-6 is uniquely qualified to determine whether the strategic plan is being implemented in a way that is resulting in true changes to highway practice. Likewise, the FRP manufacturers must be represented because they have a direct understanding of the upstream issues involved in providing the technologies to the marketplace. The AASHTO Highway Subcommittees on Materials, Construction, and Maintenance could also be included for state DOT representation. Federal agency groups include FHWA, NSF, DOD, and the National Institute of Standards and Technology (NIST). Academic and private-sector participation should be similar to that in TRB committees. A rotation schedule for committee membership will be important.

*Tactics:* The only action required under this element is to assign a specific group responsibility for a semiannual review of the strategic plan. The group should determine, based on information provided by the umbrella group as well as other means, whether performance measures are being met, whether the key elements of the strategic plan remain valid, and, if not, what revisions to the strategic plan (e.g., content, schedule, resource requirements, and/or performance measures) are necessary. This semiannual meeting would mimic, to some extent, the semiannual meetings held by AISI/American Institute of Steel Construction (AISC) and the Technical Committee for Steel Design (T-14) of the AASHTO Highway Subcommittee on Bridges and Structures because it would provide time for a structured discussion of market and technological issues, current and pending research, and updates on practice issues.

The membership of the strategic plan steering committee should be determined by the umbrella group very early in the process. A group of approximately 12 members would be ideal because it would be large enough to provide wide-ranging representation of expertise and industry areas but small enough to allow expedient course corrections related to the strategic plan. (It is possible that this group could serve as an executive council to the umbrella group.) It is important that attempts be made to include representation from the original project panel for NCHRP Project 4-27 to provide both a historical context to the work and continuity in the early years. In addition, it is advisable that one or more members of the research team for NCHRP Project 4-27 participate in this group in the early years, especially to provide guidance related to changes in schedule or performance measures. Finally, efforts should be made to "piggyback" meetings with those of other industry or professional groups to minimize travel costs and other expenses.

*Schedule:* The group should be constituted and a "kickoff" meeting held in the very early stages of the life of the umbrella group (approximately 6–8 months after the end of NCHRP Project 4-27); after that, meetings should be held approximately every 6 months.

*Resource requirements:* It is anticipated that the work of the group would be volunteer and that the only real costs of this activity would be those associated with the semiannual meetings. A staff member from the umbrella group could serve as facilitator and secretary. Thus, costs are estimated to be on the order of $30,000 per year.

*Performance measures:* The performance measures for this element are the following:

- Quickly determining group membership and scheduling the first semiannual meeting.
- Successfully conducting the semiannual meetings of the group.
- Developing a consensus resolution from the group at the conclusion of each meeting that either states that activities related to the strategic plan appear to be on schedule and appropriate for continuation or suggests a set of revised strategic plan elements (along with revised lead participants, tactics, schedules, and resource needs). This consensus statement should be circulated among the constituencies of the FRP and highway communities to encourage confidence and provide information within the industry.

**A Study of the Relative Costs of FRP Versus Traditional Materials**

*Background/description:* An unbiased economic study synthesizing current costs and predicting future ones should be developed to determine the cost-effectiveness of FRP composite material applications relative to applications using traditional materials. The cost study should concentrate on the five applications covered by the white papers presented in this report (see Appendix D). The costs of sample projects which implement the white-paper applications using traditional materials and using FRP composite materials should be compared. All assumptions made in arriving at future costs of both FRP composite materials and traditional materials must be fully documented. First costs as well as life-cycle costs should be considered and compared.

Cost studies add credence and buy-in to any long-term plan related to technology. There are concerns regarding the accuracy or completeness of many informal cost studies presented by FRP composite material advocates. There are also concerns that some in the highway industry may erroneously perceive higher costs for FRP than what is potentially achievable in the near term through an effective implementation plan and schedule. The proposed cost study must bridge the gap between the civil-infrastructure community's perception of an intolerably high cost for FRP materials and the FRP community's potentially over-optimistic projection of lower future costs for the materials.

Although the marketplace will ultimately judge the cost-effectiveness of FRP composite materials in the highway infrastructure, the cost study should be initiated as soon as possible to avoid wasting resources on technologies or applications if their cost-effectiveness or their potential for cost-effectiveness is not clear. An example of wasted resources on a product ultimately proven not to be cost-effective is the aborted introduction of aluminum bridge decks by Reynolds Metals and High Steel Structures. Obviously, cost-effectiveness in the short term is not necessary, but, in the long term, it is essential. Life-cycle costing concepts should be used as much as possible, but within reason. The effective service life of typical highway bridges has been shown to be about 60 to 75 years, based on functionality. Bridge components projected to last much longer may not be necessary.

It is unlikely that the cost study would find the use of FRP totally unwarranted in every potential application; accordingly, although some FRP applications presented in the strategic plan may not prove cost-effective, it will be worthwhile to pursue other applications and activities presented in the strategic plan. The cost study has as a major goal proving the underlying assumption that moving forward with FRP is, at least on face value, a good idea from an economics perspective.

*Lead participants:* This applied study should be sponsored by AASHTO, perhaps as a relatively low-cost and quickly accomplished project. The contractor should be equally familiar with the applications of both traditional materials and FRP composite materials in the highway infrastructure and be unbiased. Steering committee members should be represented on the project panel.

*Tactics:* The AASHTO Highway Subcommittee on Bridges and Structures, perhaps in concert with other AASHTO subcommittees, should request an NCHRP Project 20-7 task study immediately. The objective of the cost study would be to quickly assess, on a representative basis, the costs of design, construction, and maintenance of the highway applications noted in the white papers that are part of this report. When good cost data are not available, estimates should be used. These costs should be presented in a unit of measure that is comparable among applications, such as a dollar per square foot of structure rehabilitated. It is essential that the cost study not rely on reported costs that are incomplete—for example, project costs that do not explicitly account for donated materials or components or for in-kind services from DOTs or other construction units. It may be necessary for estimates of real costs to be included for cases in which services or products were donated. The cost study may require cost projections based on the best available knowledge, and it is important that the report clearly differentiate among estimates, projections, and hard data.

Although Project 20-7 tasks are often overseen solely by task panels composed of AASHTO and FHWA members, it is recommended that the task panel for this study include membership from the FRP community to ensure balance and to enhance access to information. Moreover, it is recommended that the study team contracted to do the project include members with expertise in both highway projects (for cost comparisons with traditional construction materials and methods) and FRP technologies.

*Schedule:* The request for a cost study should be made immediately at the conclusion of NCHRP Project 4-27; endorsement by the entire AASHTO Highway Subcommittee on Bridges and Structures and possibly other subcommittees should be sought to help ensure that the AASHTO Standing Committee on Highways funds the cost study. It is estimated that the cost study will take approximately 1 year once a research team is under contract.

*Resource requirements:* The request for the cost study can be made through the efforts of state DOT members. The estimated cost of the study is $60,000.

*Performance measures:* Obtaining funding for the cost study within 6 months of completion of NCHRP 4-27 is the first performance measure for this element. A second is completion of the cost study within the contracted time frame. Finally, as new projects are designed, built, and maintained, the umbrella group or others should attempt to see how the costs of these projects relate to the costs of projects that were the basis for the cost study. One measure of the quality and accuracy of the cost study will be looking at how closely the costs documented by the cost study match the growing database of costs.

**A Database of Practical Infrastructure-Based FRP Knowledge**

*Background/description:* As a result of FHWA's IBRC program, the number of applications of FRP composite materials in the highway infrastructure grows yearly, yet the body of knowledge on these materials has not kept pace. Although the states evaluate the success of their individual projects, no mechanism currently exists to gather, quantify, and synthesize the collective results of these demonstration projects into a coherent body of knowledge.

The proposed project would involve taking a critical look at the demonstration projects from the IBRC as well as other FRP projects to date and quantifying the degree of their success in a collective database. A report that summarizes the results of this critical analysis (and thus the projects themselves) should contain appropriate performance measures for the FRP applications, the benchmarks that the FRP technology was intended to meet, and a detailed description of how well (or poorly) the technology has performed relative to the benchmarks. Some of the performance measures should allow cross comparison of FRP technology with other technologies. The availability of reports (generated from database information) that describe how the FRP projects performed collectively would allow states to share information, FHWA to better choose new demonstration projects, and designers to refine subsequent designs. The synthesis of results would also provide validation of the program.

As noted above, it would be useful if, along with a detailed set of data related to FRP applications, a set of data could be developed that would enable new technologies to be compared with each other. For example, there should be certain parameters measured that are applicable to all technology demonstration projects (both IBRC and non-IBRC), whether they involve high-performance steel (HPS), high-performance concrete, FRP, corrosion-resistant rebar, or other technologies. Care should be taken to differentiate "proof of technology" data from data that might be used to help assess the use of FRP as an alternate construction material on a regular basis on conventional projects.

*Lead participants:* FHWA should be encouraged to develop a project to accomplish this important task, with either FHWA personnel or an outside consultant. State DOT input regarding the parameters to measure for FRP and for all IBRC technologies should be sought.

*Tactics:* The state DOTs, the FRP industry, and others should encourage FHWA to undertake the database project indicated. If FHWA pursues such a project, it is highly recommended that a guidance panel with members from U.S. DOT, the state DOTs, the FRP industry, and the research community draft a set of guidelines regarding the types of data that are needed so that the consultant or project leader can use the guidelines as a baseline for augmentation and improvement. The project requirements should include broad dissemination of the data, coordination with non-FRP IBRC technologies and non-IBRC projects, and posting of information on the FHWA Web site, as appropriate. The results of the project should also be made freely available to the umbrella group. Although the database should be updated regularly, it will be useful if an annual report is generated that can provide an appropriate and regularly occurring snapshot of performance with respect to the project. Professor David Hartgen's annual report of state-by-state performance of roadways may be a useful resource document on which to base this database effort; however, in this case, projects and technologies rather than states would be compared (for additional information related to the comparative approach, see Hartgen, D. T. and N. J. Lindeman, "Emerging Gaps in Highway Performance Between States and Road Classes During the ISTEA Years," *Transportation Quarterly,* Vol. 54, No. 1, 2000, pp. 35–53).

Finally, it would be useful if the enacting regulations for the IBRC programs in the future could require that state DOTs provide the data that are deemed important and report them in the manner prescribed by the project leader. Similarly, the states should collectively consider endorsing a unified reporting approach for their non-IBRC demonstration projects so that these data will be easily combinable with others.

*Schedule:* Because this plan element will provide useful information regardless of how other elements of the strategic plan fare, it is recommended that this effort be initiated at the conclusion of NCHRP Project 4-27. It should then continue at least as long as the IBRC program continues and perhaps several years longer to capture additional performance data.

*Resource requirements:* Developing an agreed-on set of data to be collected and a framework in which the data will be analyzed and presented will not be a trivial effort, and this must occur in the initial year of the project. In addition, the first year will require a substantial data collection effort that includes ferreting out the appropriate sources of data and looking at historical documents for IBRC projects that have been completed but for which important data may not have been captured. In future years, even though the complete list of finished projects will have to be revisited and the annual allotment of new ones reviewed, the project should be less costly because the performance data should be fewer and easier to obtain after the initial year. Funding recommendations are the following:

- Year 1: $125,000,
- Year 2: $100,000, and
- Year 3 and continuing: $75,000.

*Performance measures:* The following are performance measures proposed for establishment of the database:

- Months 6–12: FHWA should initiate the project.
- Year 1 of the project: The project report should include at least 75 percent coverage of past IBRC projects; a framework for collection of data for all past, current, and future projects; and an easily usable database of information that is readily available on the FHWA Web site.
- Year 2 of the project: The project report should include at least 85 percent coverage of past IBRC projects and 90 percent of all current projects for which data are available.
- Year 3 and beyond: The project report should include updates of at least 90 percent of past IBRC projects and 90 percent of all current projects for which data are available.
- Year 1 and continuing: Reference to the project should show up in the activities of the umbrella group, and a significant number of "hits" should be recorded on the FHWA Web site.

## Generic Bridge-Specific Material Specifications

*Background/description:* The designer-material nature of FRP composite materials is not amenable to the highway infrastructure design culture. A generic material specification specific to highway infrastructure applications should be developed through a research project. The project deliverable would be a practical material specification suitable for consideration by ASTM and AASHTO. The research contractor should be equally familiar with the FRP composite material producer community and the highway infrastructure design community.

A generic material specification is one that many fiber and resin producers should be able to meet with their varied product offerings or with a slight modification to their offerings. In this way, it would be similar to the structural steel specifications for bridge steels. The ASTM A709 specification is met by all of the interested steel producers from Bethlehem Steel to United Steel. The steel specifications are developed through the AISI, the steel-producers association representing all major U.S. producers. The lack of successful engagement of the highway-infrastructure community by an FRP-producer group warrants the development of a usable material specification by the infrastructure community itself. Similarly, the proposed FRP composite material specification should be generic; it should apply to all structural FRP applications in the highway infrastructure. This vision of the specification is again similar to the ASTM A709 specification, which has superseded ASTM A36, A572, A588, and so forth, and applies to all structural steel applications for bridge design through its various grades (most recently incorporating HPSs). Research would be required to determine whether a single specification could adequately address both fiberglass- and carbon-composite materials. A single specification would be desirable because it would parallel the approach used with steel. It is probable that several related efforts would contribute to development of the specification.

Ongoing FHWA-sponsored research at the University of Wisconsin is developing material specifications to qualify FRP laminates based on minimum performance targets and to accept FRP components based on consistency in achieving targets. Simultaneously, FHWA is sponsoring a joint effort at the Georgia Institute of Technology and West Virginia University to develop standards and test methods to qualify FRP deck and FRP superstructure materials and products for highway bridges. Whether these efforts will achieve the far-reaching goal of qualifying FRP laminates and accepting them based on consistency of performance is currently unknown. The research is being conducted by some of the most respected FRP researchers and holds much promise. If the project deliverables from the ongoing FHWA projects meet these goals, the proposed effort to generate generic bridge-specific material specifications should be redirected into an evaluation of the proposed material specifications. (An evaluation should include trials to compare hypothetical applications of the specifications with practices used in successful demonstration projects to date.) Otherwise, the FHWA projects represent an excellent starting point for this proposed work. NCHRP Project 10-55, “Fiber Reinforced Polymer Composites for Concrete Bridge Deck Reinforcement,” is developing a material specification for reinforcing bars made from FRP. This work should also become a part of the proposed larger material-specification effort.

*Lead participants:* The applied and specific nature of the proposed specification suggests that NCHRP would be the natural sponsor of this effort. AASHTO committees, as noted below, would have a lead role in originating the research.

*Tactics:* The AASHTO Highway Subcommittee on Materials, in conjunction with the Subcommittee on Bridges and Structures, should consider developing and endorsing (for consideration for NCHRP funding by the AASHTO Standing Committee on Research [SCOR]) the proposed project. These groups should also encourage NCHRP project panel participation by their members if the project is undertaken.

*Schedule:* The umbrella group should co-develop a Stage 1 research problem statement with the AASHTO subcommittees as soon as practical after endorsement of the strategic plan. The project itself would probably commence within 12 to 24 months thereafter, with completion expected approximately 5 years from the end of Project 4-27.

*Resource requirements:* An investment in volunteer staff time among state DOT members would be required to prepare the research statement and champion it through the NCHRP process. This might require 10 to 20 person-hours of effort. Additional volunteer time would be required, as is usually the case, for panel participation by state DOT, FHWA, academic, and industry members. The project funding estimate would be in the $500,000 to $1,000,000 range. The actual cost would depend, in part, on how much information becomes available from current efforts. It may be possible that the $500,000 would be fragmented among several research efforts and that a capstone project that synthesized existing or new findings into a single specification might be possible for approximately $200,000 to $300,000.

*Performance measures:* The performance measures for the development of generic bridge-specific material specifications are the following:

- Year 1: Development and endorsement of the Stage 1 NCHRP statement.
- Year 2: Selection of the statement for funding by AASHTO’s SCOR and project initiation,
- Years 3–5: Achievement of confidence among the NCHRP panel regarding the perceived and actual outcomes of the NCHRP project.
- Years 5–7: AASHTO adoption of the specifications, ASTM adoption of the specifications.

## Generic Bridge-Specific Design and Evaluation Methodologies

*Background/description:* Highway infrastructure designers typically simplify complex material and component behavior through various idealizations. A research project should be developed with the ultimate goal of delivering design and evaluation provisions to be considered by AASHTO for inclusion in their bridge design and condition-evaluation (i.e., rating) manuals. The research contractor would need knowledge of FRP composite material design applications as well as traditional bridge design.

The resultant methodologies and the provisions based on the idealizations of the methodologies should not only simplify the complex behavior of FRP materials but also acknowledge the nature of their behavior. A good example of traditional material behavior idealization is the Whitney stress-block idealization of the behavior of concrete in compression. The methodologies developed in this task must acknowledge the linear-elastic behavior of FRP composite materials to failure.

As part of NCHRP Project 12-42, "LRFD Bridge Design Specifications Support," the research contractor developed an editorial guideline and a technical guideline for the incorporation of new materials into the *AASHTO LRFD Bridge Design Specifications.* The technical guideline provides background on calibration issues as well as the types of information that must be included in a specification to make it consistent with the conventional structural materials already included in the document. These documents have been disseminated to the AASHTO Highway Subcommittee on Bridges and Structures by NCHRP.

It is expected that the proposed project will rely heavily on the results of past and ongoing research sponsored by FHWA, NSF, AASHTO, individual state DOTs, and the FRP industry. The project may be broken into separate parts or phases—one phase that can be initiated soon, based on current knowledge and practice, and a second phase that would be a revision based on the results of the generic FRP materials specification noted above.

Ongoing FHWA-sponsored research (being performed jointly at the University of Wyoming, Pennsylvania State University, and the University of Missouri at Rolla) is developing design and construction specifications for bridge components prestressed with FRP tendons. FHWA-sponsored research at the Georgia Institute of Technology and West Virginia University is also developing standards and test methods for accepting FRP decks and deck superstructures that could become a part of the AASHTO construction specifications. The research is being conducted by some of the most respected FRP researchers and holds much promise. If the project deliverables from the ongoing FHWA projects meet the goal of delivering design and evaluation provisions for FRP, the effort to develop generic bridge-specific design and evaluation methodologies should be redirected to include an evaluation of the proposed design and construction specifications. (An evaluation should include trials to compare hypothetical applications of the specifications with practices used in successful demonstration projects to date.) The FHWA projects are an excellent starting point for this proposed work. In any case, much additional work is required to generate a complete FRP section of the *AASHTO LRFD Bridge Design Specifications* (comparable to the concrete and steel sections) and FRP sections of the AASHTO condition evaluation (i.e., rating) manuals.

*Lead participants:* The applied and specific nature of the proposed specification suggests that AASHTO would be the natural sponsor of this effort (through NCHRP). AASHTO committees, as noted below, would have a lead role in originating the study.

*Tactics:* The AASHTO Highway Subcommittee on Bridges and Structures should consider developing and endorsing (for consideration for NCHRP funding by AASHTO's SCOR) the proposed project.

*Schedule:* The umbrella group should co-develop a Stage 1 research problem statement with the AASHTO subcommittees as soon as practical after endorsement of the strategic plan. Phase 1 of the project (using current practice and knowledge) would probably commence within 12 to 24 months thereafter, with completion within approximately 4 years from the end of Project 4-27. Phase 2 (which would rely on the generic materials specification) might commence around Year 5 and be complete around Year 7.

*Resource requirements:* An investment in volunteer staff time among state DOT members would be required to prepare the research statement and champion it through the NCHRP process. This may require 10 to 20 person-hours of effort. Additional volunteer time would be required, as is usually the case, for panel participation by state DOT, FHWA, academic, and industry members. The project funding estimate for Phase 1 would be approximately $350,000; for Phase 2, it would be approximately $100,000.

*Performance measures:* The performance measures for development of generic bridge-specific design and evaluation methodologies are as follows:

- Year 1: Development and endorsement of the Stage 1 NCHRP statement.
- Year 2: Selection of the statement for funding by SCOR and project initiation.
- Years 3–4: Achievement of confidence among the NCHRP panel regarding the perceived and actual outcomes of Phase 1 of the NCHRP project.
- Years 5–6: AASHTO adoption of the specifications.
- Years 5–7: Initiation and completion of Phase 2 of the project.
- Years 8–9: AASHTO adoption of the specifications.

## Generic Bridge-Specific Inspection and Repair Methods

*Background/description:* The ongoing investigation into the recent crash of American Airlines Flight 587's Airbus A300-600R has focused renewed attention on the inspection and repair of structural components made of FRP composite materials. The U.S. highway infrastructure gets much less frequent and less intense inspection than commercial aircraft. If inspection and repair of commercial aircraft is difficult (as suggested in the media after the tragic accident), the problem will be amplified for the less-scrutinized and less-frequently maintained highway structures. Relatively simple inspection and repair procedures must be developed for FRP applications in the highway infrastructure.

Ongoing FHWA-sponsored research being performed jointly at the University of Missouri at Rolla is developing design and construction specifications for bonded FRP repair of concrete structures. The research is being conducted by one of the most respected FRP researchers and holds much promise. If the project deliverables from the ongoing FHWA project meet the goal of developing design and construction specifications for FRP, the effort to develop generic bridge-specific inspection and repair methods should be redirected to include an evaluation of the proposed design and construction specifications. (An evaluation should include trials to compare hypothetical applications of the specifications with practices used in successful demonstration projects to date.) The FHWA project is an excellent starting point for this proposed work. In any case, additional work is required for other repairs.

Under NCHRP Project 10-59, "Construction Specifications for Bonded Repair and Retrofit of Concrete Structures Using FRP Composites" (currently pending), construction specifications and a construction process control manual are under development to ensure performance as designed of bonded FRP repair and retrofit of concrete structures. The deliverable for this NCHRP project should be incorporated into the larger proposed effort for all highway-infrastructure applications. It is hoped that the FHWA and NCHRP efforts are complementary.

*Lead participants:* FHWA should develop inspection techniques practical for application within the existing culture of the highway infrastructure. Given FHWA's long history with the development of bridge inspection technologies and its concomitant role in educating/training DOT staff in the use of highway technologies, it may be most appropriate for this to be primarily an FHWA-led effort.

*Tactics:* The AASHTO Highway Subcommittee on Bridges and Structures should consider endorsing (for consideration by FHWA) the proposed project, and FHWA may want to consider incorporating this effort into its overall plans for research. It is desirable for the project not only to refine and document the technologies and procedures for inspection of FRP structures but also to prepare a showcase and training program that covers the included technologies (which could become one of the offerings of the National Highway Institute [NHI]). The project should rely heavily on the substantial research already conducted by FHWA, NCHRP, and others.

*Schedule:* Because FRP structures are already in place, there is a substantial and immediate need for this research and the development of associated technology transfer. Accordingly, the project should be initiated immediately, and it is estimated that it would take approximately 18 to 24 months to assemble inspection and repair information based on best current practice and knowledge. It will be necessary, through additional research, to develop or refine additional technologies.

*Resource requirements:* The project funding estimate for assembling information in a useful report/document is approximately $125,000; development of appropriate technology transfer materials (perhaps a draft workshop with training materials) is estimated at $75,000.

*Performance measures:* The performance measures for development of generic bridge-specific inspection and repair methods are the following:

- Year 1: Initiate the project.
- Year 2: Complete the project and disseminate results.
- Years 3–4: Conduct at least three training sessions through the NHI or a similar entity.
- Years 5–6: Conduct at least four training sessions through the NHI or a similar entity.
- Experience initial growth and then continuing numbers of "hits" on the FHWA Web site dedicated to disseminating information from the project.
- Years 6–7: Obtain at least one "return customer" from a previous training course to learn any new, updated information as the course is continuously upgraded.

## Training on FRP Composite Materials for Practicing Engineers

*Background/description:* Bridge designers and owners must become more familiar with and better understand FRP composite materials. Designers obviously must understand the behavior and design of components made of FRP composite materials to encourage widespread usage of these materials in the highway infrastructure. Materials and construction engineers working for state DOTs must also be made aware of the specification and construction issues that are unique to FRP. Perhaps more importantly, however, *decision-makers* must also understand these issues.

For bridge owners, one suggestion is to build on the series of workshops that the short-lived federal Managers' Working Group (FMWG) held a few years ago. Bridge owners need to hear how a program to develop and use FRP composite products works in practice from those who have already been involved in such programs (in aerospace, marine, and automotive applications). The FMWG workshops were informal gatherings of federal program managers from DOD, the Department of Energy, U.S. DOT, and NIST to exchange information on time frames, budgets, overcoming technical obstacles, and working with the industry. Because of retirements, it would be difficult to assemble the precise group again, but it would be worthwhile as a one-time workshop at meeting of the AASHTO Subcommittee on Bridges and Structures.

For designers and specifiers, training on the use of the newly developed specifications is in FHWA's research and development plan, but this is subject to the vagaries of the federal budget process. It would be helpful to have a call for such training from this outside group.

*Lead participants:* NHI should develop a training course and associated educational materials (e.g., primers and handbooks) to teach bridge owners, designers, and inspectors about the application of FRP composite materials in the highway infrastructure. Groups such as ACEC and the National Society of Professional Engineers may serve as disseminators of information related to FRP training opportunities. The Associated General Contractors (AGC) and union groups should both be encouraged to develop training programs related to the construction of FRP highway structures.

*Tactics:* Initiate development of an NHI suite of courses related to FRP. The suite should have three separate audiences:

- **Owners:** For this audience, higher-level information related to benefits, problems, and trends related to FRP should be included in the course. This would be at most a ½-day session, and it might be possible to transmit much of this information through written material or on video.
- **Designers and Specifiers (including materials engineers):** For this audience, specific structure design information should be included in the course, and it should mimic, to the extent practical, other NHI highway design courses in format and philosophy.
- **Inspectors:** For this audience, a course that can be broken into two delivery methods should be investigated. First, an "add-on" version that can be appended to existing bridge inspection training should be developed. Second, a "standalone" version should be promoted, perhaps with more in-depth coverage of FRP as a material and of the special issues associated with FRP. It is probable that the standalone version will be more highly desirable in the early stages of FRP integration into the highway infrastructure, when states have fewer structures in their inventory and can dedicate specific staff to in-depth evaluations. Eventually, the goal should be to have the add-on version be typical, as FRP structures are seen in the same light as other materials.

State DOTs should effectively team with their local private-sector design community to promote participation in NHI courses and the dissemination of information through other channels. Inclusion of organizations in the International Bridge, Tunnel, and Turnpike Association (IBTTA) is also essential, given the nature of the structures that these organizations often manage and their need for the perceived benefits exhibited by FRP. The umbrella group would be an obvious primary repository of available sources of training and should be seen as the "go-to" organization for "one-stop shopping," whether one is from the private or public sector or from the design side or the construction side.

*Schedule:* Although these courses may be desirable immediately, they will be most useful if they can be developed so that their content will not change drastically within the first few years because of the outcomes of other strategic plan elements. Accordingly, although planning for the courses can be initiated immediately, it may be desirable to develop the owners' portion in the near term (perhaps within a year after completion of NCHRP Project 4-27) because that portion may benefit from inclusion of information on recommended efforts described in the strategic plan that are planned or underway (e.g., it might help to educate owners on how they fit into the processes that will keep momentum alive in the FRP integration process). It may be best to develop the design and inspection courses for when compilations of design and inspection methods result from some of the projects mentioned in other elements of the draft strategic plan. The courses would be offered on an as-scheduled basis indefinitely.

*Resource requirements:* The costs to develop the course modules may vary significantly depending on the outcome of the projects that will provide information on design and inspection methods. The owners' module is much more modest, and it may be developed (including a master set of associated documents, some of which may be computer-based) for approximately $60,000.

The costs to conduct the courses should be similar to courses already conducted by NHI, AGC, or others.

*Performance measures:* The performance measures for developing training for practicing engineers on FRP composite materials are as follows:

- Development and conduct of trial version(s) of the courses.
- Delivery of NHI courses to at least three agencies per year for the first 2 years following completion of course development.
- Dissemination of information on the owners' module to major FHWA units, state DOTs, IBTTA members, and ACEC within 2 years of the completion of NCHRP Project 4-27.

## Education on FRP Composite Materials for Graduate Civil Engineers

*Background/description:* Graduate civil engineers entering the highway infrastructure job market must be prepared to design using FRP composite materials to ensure more widespread usage of these materials. Most civil-engineering departments across the country—although teaching courses in steel, concrete, and perhaps wood structures—do not offer structural design courses applying FRP composite materials. Introducing new courses at a college or university is not an easy task, and there is increasing pressure to reduce the number of credits required for graduation. Further, course development is a major task for faculty members burdened with research requirements. Most likely, a complete course on design with FRP composite materials is not possible or necessary for all institutions. A module introducing FRP design included in a design course on steel and concrete may be more easily integrated into curricula.

Curriculum development beyond the basic introduction to FRP design envisioned above could involve a two-course sequence. A prerequisite or concurrent course would have to be taken in graduate-level Structural Mechanics. The first semester would deal early on with the basics of FRP composites, but move on to the main subjects of viscoelasticity and anisotropic material analysis. A laboratory section would cover fabricating simple specimens and basic mechanical behavior. The second semester would cover environmental and long-term behavior issues, including either a laboratory section covering accelerated testing or a design project depending on whether the student plans on going into research or practice.

*Lead participants:* The NSF and the U.S. Department of Education should be encouraged to sponsor a curriculum-development project to develop undergraduate courses in structural design using FRP composite materials or a module related to FRP for courses that cover multiple materials. The proposed undergraduate course (or course module) should be analogous to the traditional introductory courses in structural design of steel or reinforced-concrete members. Aspects of the curriculum-development project may also be more easily introduced into other general courses such as traditional construction materials courses. Because the majority of civil engineers enter the building-structures market, the course should include applications in both buildings and bridges; this will help to ensure the cross-market understanding currently enjoyed by wood, steel, and concrete. The curriculum-development project also would use the results of the proposed NCHRP projects dealing with material specifications and design-and-evaluation specifications. As such, it should not be initiated until those efforts are complete and the resultant specifications are adopted by AASHTO. Because of the importance of "educating the educators," industry organizations should be encouraged to participate with the development of design aids that would facilitate instruction for both professors and students.

*Tactics:* Because curriculum development is often responsive to market needs, AASHTO should be encouraged to formally approach NSF and the U.S. Department of Education regarding the perceived need for curriculum development. NSF and the U.S. Department of Education should move forward with a blue-ribbon panel discussion on the best methods for inclusion of FRP in curricula. Discussions should cover school offerings at the university undergraduate level (bachelor's degrees in civil or architectural engineering) focusing on buildings, bridges, or both, and on the college technical level (associate degrees in civil- or architectural-engineering technology). In addition, AASHTO and FHWA may want to formally interact with the Accreditation Board on Engineering and Technology (ABET), emphasizing the perceived desirability for programs accredited by the Engineering Accreditation Commission and Technology Accreditation Commission to include coverage of FRP and to instill in students the ability to address issues related to new materials through lifelong learning. The umbrella group should attempt to implement informational workshops for professors similar to those sponsored by TMS, AISC, and the American Concrete Institute for masonry, steel, and concrete, respectively. To measure the increased coverage of FRP over the years, an initial survey should be conducted by the umbrella group to determine the level and extent of FRP technology covered in civil/architectural engineering programs currently. Thereafter, follow-up surveys can be conducted every third year.

*Schedule:* Because a coherent understanding of what issues are important and what information is or will soon be readily available is imperative before any curricula are set, this curriculum development effort should commence approximately 3 years after completion of NCHRP Project 4-27.

*Performance measures:* The performance measures for development of education on FRP composite materials for graduate civil engineers are the following:

- Initial contact with NSF and the U.S. Department of Education by AASHTO and FHWA within 2 years.
- Initial contact with ABET by AASHTO and FHWA within 2 years.
- An initial survey of engineering departments on current coverage of FRP within 2 years
- Convening of a blue-ribbon panel on inclusion of FRP in college curricula within 3 years, with published findings and recommendations for widespread distribution.
- Development of a sample course (and course module) by the end of Year 5.
- A follow-up survey of engineering departments on current coverage of FRP every third year after the initial survey, with measured increases in coverage for 10 years.

**Continuation of FHWA's Innovative Bridge Research and Construction (IBRC) Program**

*Background/description:* The United States Congress should be made aware of the important nature of FHWA's IBRC program and encouraged to extend this important program beyond its current funding. Reports of the synthesis of the IBRC program demonstration projects, published by FHWA, should prove the value of continuing the program.

*Lead participants:* FHWA and AASHTO should take a lead role in informing Congress of the benefits of the IBRC program.

*Tactics:* It is essential that AASHTO, its member states, and others provide information to both U.S. DOT and the U.S. Congress about the perceived usefulness of the IBRC program as federal transportation legislation is drafted. This support could include letters that also encourage the action described in the strategic plan element, "A Database of Practical Infrastructure-based FRP Knowledge." Such action might result in the politically desirable discussion of a future ability to provide validation of the program; this would demonstrate to Congress the merits of its decisions to provide funding. Requirements related to the development of performance measures, benchmarks, and evaluation data, as mentioned in "A Database of Practical Infrastructure-based FRP Knowledge," should be part of the requirements within the program.

*Schedule:* This effort should start 12 months after the conclusion of NCHRP Project 4-27 and continue indefinitely. (Work should be undertaken to ensure inclusion of IBRC in the next surface transportation act, yet it may be advisable to have the results of the strategic plan element, "A Database of Practical Infrastructure-Based FRP Knowledge," for maximum effect.)

*Resource requirements:* The request for the study can be done through the efforts of state DOT members and other interested parties. No formal funding is required.

*Performance measures:* The performance measure for this element is the submission to FHWA (and others) of letters of support for the IBRC program from AASHTO (and others) before enactment of new federal transportation legislation.

# APPENDIX D

# WHITE PAPERS

## INTRODUCTION

The dictionary defines white papers as position papers that typically present an objective overview of the state of the art in a specific technology. White papers have much in common with executive summaries. The term “white paper” originally derives from the United Kingdom, where a more extensive treatment of a subject is called a “blue book.”

The following white papers present a frank assessment of the current situation of the proposed application of fiber reinforced polymer (FRP) composite materials to the highway infrastructure. These white papers also present a frank assessment of FRP’s potential to successfully penetrate the marketplace and a recommended path forward within the context of the draft strategic plan presented in Appendix C of this report.

FRP composite materials are lighter in weight and may prove more durable than the traditional highway infrastructure construction materials of steel and concrete. These advantages come with an increased initial cost. The following white papers explore how the attributes of more durability and lighter weight can be used to advantage to improve the nation’s highway infrastructure in the near-term future.

Each of the white papers may address the following topics (in no particular order) as relevant to the stated application:

- Design requirements,
- Design methods,
- Material selection criteria/engineering properties,
- Fabrication/construction,
- Quality assurance/Quality control (QA/QC),
- Cost-effectiveness,
- Training,
- Metrics for success, and
- Inspection and maintenance.

The application of FRP composite materials to the highway infrastructure should be done in an integrated manner, much as concrete and steel are handled through a single section of the *AASHTO LRFD Bridge Design Specifications*, Sections 5 and 6, respectively. As such, the final strategic plan should reflect the five highlighted applications but also be relevant to other applications. Also, a specific strategic plan should not be developed for a single application. FRP composite materials and their resistance and material provisions should be treated identically from application to application. Similarly, cultural issues such as training should be dealt with in an integrated manner.

It is worth noting that other potential applications for FRP were investigated under NCHRP Project 4-27, notably guiderail and highway signage. However, the cost-to-potential payoff for these applications was considered smaller than the five technologies chosen, and some had technological issues (e.g., the dynamic response and repairability of FRP guiderail) that were deemed too great to overcome in the near term.

# WHITE PAPER 1: REHABILITATION OF CONCRETE STRUCTURES USING FRP COMPOSITES

This white paper focuses on applications of externally bonded FRP composites to concrete transportation structures, specifically, the use of externally bonded FRP laminates to control spalling and/or cracking or to provide flexural strengthening, shear strengthening, and increased axial load capacity. Seismic applications of externally bonded FRP laminates to concrete structures are addressed in "White Paper 3: FRP Composites for Seismic Retrofit of Concrete Bridges."

In the aging transportation infrastructure of the United States, there are many instances in which structural repair or rehabilitation is needed. Traditionally, substantial repair or rehabilitation of concrete elements has been relatively difficult to achieve. Externally bonded FRP laminates offer an effective and cost-competitive technique. Furthermore, relative to some other FRP uses, this particular application, along with a closely related application involving seismic wrapping of columns, is probably the most mature of the promising areas identified by the five white papers. Because of the high cost of replacing structurally deficient structures, the relatively high material cost of FRP is offset greatly by the enormous benefit of being able to quickly and effectively repair an existing structure. Furthermore, often the ease of installation of FRP laminates more than offsets the increased material costs for concrete structures. The economic benefits of this application of FRP, combined with its success to date, have led to the relatively widespread use of this new repair technique.

Some of the first work involving applications of FRP composites to civil structures (dating back to the 1980s) involved the repair and retrofit of concrete structures using externally bonded FRP laminates. This technology is relatively mature, with extensive research results detailing bond performance, creep effects, ductility of the repairs, fatigue performance, force transfer, peel stresses, resistance to fire, ultimate strength behavior, and analytical methods. Today, there are numerous manufacturers that provide readily available FRP composite systems utilizing carbon, glass, and aramid pre-cured pultruded plates and uncured sheet systems. As will be discussed, these manufacturers have produced design and installation guidelines for generic applications. The most extensive application has been to buildings and parking garages, although numerous bridge-related repairs have been conducted. 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 (FRP laminate applications). In the hundreds of installations of this type throughout the world—which include crack control, spall control, flexural and shear strengthening, and increased axial load capacity—the technology has proven quite effective, with few problems.

## DESIGN REQUIREMENTS

This application of FRP involves either the repair or retrofit of an existing concrete structure. The four limit states applicable to bridge design are service, fatigue and fracture, strength, and extreme event. The three limit states that are relevant here are service (in terms of spalling and/or crack control); fatigue and fracture (in terms of having adequate fatigue behavior); and strength (in terms of flexural, shear, or axial capacity enhancement). In determining the design requirements for a specific application, the following question needs to be asked: What is the goal of the repair or retrofit? The most common answers to this question are crack control, control of spalling, flexural strengthening, shear strengthening, or increased axial load capacity.

In all cases, the bonded FRP laminates must be designed to have appropriate bond characteristics at both service loads and up to the ultimate strength limit state (this involves not only FRP properties, but also the properties of the concrete substrate and the bonding agent). The bond must also be durable (i.e., not adversely affected by environmental and thermal effects nor the effects of fatigue), resistant to adverse creep effects and stress rupture under sustained loads, and have acceptable fire resistance (i.e., comparable to steel and concrete structures). For applications involving crack control, the laminate must have adequate stiffness to arrest cracks. For strengthening applications, the bonded laminate must provide the needed strengthening. Appropriate design guidelines are needed to address each of these design requirements.

## MATERIAL SELECTION CRITERIA/ ENGINEERING PROPERTIES

For laminate applications, the selection of the appropriate material obviously depends on the application. For spall repair, stiffness is not as critical as it is for crack control. As such, less-expensive glass fibers may be more appropriate for spall control, whereas the more expensive and stiffer carbon fibers are recommended for crack control. For strengthening, glass, aramid, or carbon fibers can be considered. All can be used if the appropriate strengthening can be achieved. However, from a practical application standpoint, as well as economy of installation, designs resulting in a reasonable number of laminates will help determine the fiber type. In addition to the selection of fiber type, one must determine the type of system (cured plates or uncured sheets) as well as the adhesive to be used.

Regardless of the final materials selected, material specifications need to be established and satisfied. Traditional materials such as steel and concrete have specific ASTM specifications that they must satisfy to be used for bridge applications. A similar set of specifications needs to be developed for FRP laminates and the adhesives used to bond them. An FHWA research project titled “Material Specifications for FRP Highway Bridge Applications” (contract DTFH61-00-C-00020) is dealing directly with this issue as it relates to FRP composites. The results of this FHWA project will be very useful in answering the many materials and specifications questions related to FRP. One issue that has yet to be adequately addressed is the long-term properties of FRP material. No agreed-on accelerated aging tests have been established on which to base service life predictions of this type of repair. A companion report will be published with the FHWA final report and recommended AASHTO material specification. This companion report was prepared as part of FHWA’s earlier Accelerated Test study. It will summarize currently available accelerated test procedures and discuss their pros and cons.

## DESIGN METHODS

The following issues must be addressed in the development of design guidelines:

- Amount of strengthening permitted;
- Bond stress, anchorage, and delamination;
- Long-term bond durability;
- Serviceability issues;
- Effects on capacity; and
- Modes of failure and ductility.

### Amount of Strengthening Permitted

It is commonly accepted that an unstrengthened member check should be satisfied prior to making the decision to use FRP laminates to strengthen a concrete structure. The purpose of the unstrengthened member check is to ensure that the concrete element is capable of withstanding at least some amount of load over the service loads (sometimes chosen as 1.2 times the service dead load plus live load). This ensures that the member being strengthened is only partially relying on the FRP even at ultimate loads. This is an area in which additional research is needed because the current manufacturer guidelines are not consistent and are not truly calibrated.

### Bond Stress, Anchorage, and Delamination

Any design procedure for bonded laminates must address issues related to force transfer, anchorage, and delamination. These issues will depend on the application, geometry, concrete and adhesive properties, as well as the laminate used. The extensive research conducted on this topic is suitable for code development. One potential question remaining is how to use laminates that do not extend into the compression zone of the beam for shear reinforcement. Although laminates that do extend into the compression zone have proven to be quite successful, in cases in which this ability is not available, alternative solutions are needed.

### Long-Term Bond Durability

The design must address long-term bond durability as it is affected by environmental factors, thermal effects, and fatigue. Although a certain amount of research has been conducted in this area, it all involves accelerated aging tests. There is debate concerning accelerated aging tests’ validity and their ability to accurately predict service life. The numerous existing field applications are relatively young and have yet to produce long-term performance data. It is essential that the necessary reduction factors be developed to account for potential degradation of bond performance over time. To achieve this, a standard accelerated aging test procedure should be developed as is being done for material testing through FHWA’s research project, “Material Specifications for FRP Highway Bridge Applications.”

### Serviceability Issues

The design must address deflections and crack control. This has not been a topic of extensive research to date. Studies are needed to understand and develop guidelines to address these two serviceability issues.

### Effects on Capacity

Extensive research has been conducted and relationships developed to allow determination of the increase in flexural, shear, and axial load capacity caused by FRP laminates. It appears that enough information exists in this area to develop general specifications.

### Modes of Failure and Ductility

Because FRP composites behave elastically to failure, the resulting mode of failure and amount of ductility displayed by FRP composite laminate reinforced-concrete elements are issues that need to be addressed. A good deal of research addressing these issues has been conducted, and it appears that enough is known so that guidelines can adequately address these issues.

## DESIGN GUIDELINES

In order for a new material application to gain widespread use, prescriptive design guidelines are needed. As mentioned earlier, the design and application of externally bonded laminates for retrofitting concrete elements is relatively mature, and guidelines are available from many of the individual manufacturers. However, in order for the application to gain widespread use in transportation structures, a single set of AASHTO-approved, "product-independent" guidelines is needed.

In addition to the manufacturer design guidelines, the International Conference of Building Officials has developed AC125, "Acceptance Criteria for Concrete Structures Strengthened Using Fiber Reinforced Composite Systems." Although this document is geared toward seismic strengthening, it does address flexural, shear, and axial capacity effects. Furthermore, American Concrete Institute (ACI) Committee 440 has already developed ACI440.1R-01, a "Guide for the Design and Construction of Concrete Reinforced with FRP Bars." Although this guide is not specifically for transportation structures and is not dealing with bonded laminates, it is generic in terms of the materials. Finally, the new *Canadian Highway Bridge Design Code* has attempted to lay the groundwork for covering some FRP applications. These early attempts at codifying FRP composite applications provide the stepping-stones needed for introducing the technology into future bridge design codes that may be adopted by AASHTO. It should be noted that ACI developed a "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures" that directly relates to the application discussed here.

## FABRICATION AND CONSTRUCTION

In addition to the lack of a generally accepted set of design guidelines, there is no generally accepted set of fabrication and construction specifications for bonded FRP repair. Again, each manufacturer has its own recommendations. As with the case of design codes, widespread acceptance and use of this technology will be limited until a single set of guidelines, accepted by AASHTO, is developed.

It is important to note that the short- and long-term performance of bonded FRP repairs is very sensitive to the handling, mixing, application, and curing of the FRP and associated adhesive, as well as the condition of the concrete substrate. The construction process will affect the repair effectiveness, and detailed guidelines are needed to ensure proper construction technique. To address this specific issue, NCHRP Project 10-59, "Construction Specifications for Bonded Repair and Retrofit of Concrete Structures Using FRP Composites," was developed and is currently under way (as of October 2001). The successful completion of NCHRP Project 10-59 should provide the needed fabrication and construction guidelines to enable more widespread use of this application.

## QA/QC

For bonded FRP repairs, there are two QA/QC issues. One involves the materials used, and the other involves the construction process. QA/QC for the raw materials should be covered by the ASTM specifications that need to be developed for the FRP materials and the adhesives. NCHRP Project 10-59 is addressing the QA/QC issues of the construction process through the development of guidelines detailing the appropriate handling and application of the composites (fiber and resin). Additionally, guidelines for concrete substrate evaluation before bonding and guidelines for post-installation inspection are needed. Many manufacturers require that bond tests be performed on the concrete substrate to ensure that the concrete has adequate tensile capacity to develop the needed bond. After installation (once the adhesive has cured), tap tests or infrared thermography can be used to identify bond defects. Standardization of these two types of tests will help to ensure adequate quality control of the construction process. Guidelines detailing the acceptable number and size of defects need to be developed. To develop these guidelines, additional research is needed as current guides have developed these criteria in a somewhat arbitrary manner.

## INSPECTION AND MAINTENANCE

Bridge inspectors are very familiar with steel, concrete, and timber bridges. They are not, however, well equipped to inspect and maintain a bridge that uses FRP composites. Detailed inspection and maintenance guidelines need to be developed. As readily as some departments of transportation (DOTs) have been to experiment with designs that use FRP composites, very little work has been done to develop inspection guidelines. In the case of bonded FRP laminates, inspections should focus on the condition of the bond. As previously mentioned, this can be done at the time of construction or at any later time using tap tests or infrared thermography to identify bond defects. Bridge inspectors are very familiar with tap tests and simply need to be trained to hear the difference between bonded and unbonded laminates (this will be completely analogous to hearing the difference between concrete with and without delaminations). Use of infrared thermography should not be needed in most cases, but it is an established technique for scanning large areas and identifying voids beneath the laminate.

## COST-EFFECTIVENESS

In terms of cost-effectiveness, bonded FRP laminates stand to fare quite well. Unlike FRP composite decks, which are much more expensive than the traditional alternatives, application of FRP laminates is already very cost competitive. In many cases, existing methods to provide additional strength for concrete elements are quite expensive. Because FRP laminates can be so easily and inexpensively applied, if they can be designed to satisfy the design requirements, they will be cost competitive in many cases. It is likely that this is the reason that the use of FRP laminates in the building area has seen such a dramatic rise in both the United States and abroad. It is also likely that increased use will result in even lower material costs.

## TRAINING

In order to fully benefit from bonded FRP laminates, which have been largely proven to be both effective and cost efficient, education and training on several fronts is needed. Engineers and future engineers need to be trained in the behavior of composite-reinforced concrete elements. This can be achieved by developing training classes for DOT employees much like those created to teach the new *AASHTO LRFD Bridge Design Specifications.* For future engineers, textbooks treating this subject matter are needed, and the material will need to be incorporated into design classes that are taught at U.S. universities. In addition to teaching engineers how to design with FRP composites, training materials need to be created for the contractors who will install these materials and the bridge inspectors who will check the long-term effectiveness of the repairs.

# WHITE PAPER 2: FRP COMPOSITES FOR REHABILITATION OF STEEL COMPONENTS

## BACKGROUND

The costs of strengthening deteriorated steel components, with traditional or innovative materials, are largely labor and societal costs. The costs of the materials used in the rehabilitation are usually less significant. The increased costs of innovative materials such as FRP composite materials can be offset by the reduced labor and societal costs achieved by increasing the speed of construction and reducing the disruption of traffic during construction.

Applying FRP composite materials for the rehabilitation of deteriorated steel components takes advantage of two beneficial attributes of FRP: low weight and apparent durability. Durability, however, may be less of a benefit as rehabilitation projects are typically not expected to last as long as new construction. Nonetheless, this use of FRP composite materials represents a very rational application of these more costly materials.

Because the FRP plates typically used in this application weigh significantly less than comparable steel plates, handling and positioning them at the job site are simplified for the construction workers. This relative ease of handling can result in reduced construction cost and time, which is less disruptive to traffic and lowers societal costs.

## DESIGN REQUIREMENTS

The design requirements are minimal for the use of FRP to strengthen steel components. The deteriorated steel must be replaced with FRP of an equivalent stiffness. The requirements are generally unidirectional, with flanges requiring stiffening in the longitudinal direction and webs requiring stiffening in the transverse direction. More significant design requirements are needed for the adhesive bond in terms of adhesive type, bond line thickness, and development length.

## DESIGN METHODS

The non-ductile failure of FRP composite materials because of their linearly elastic behavior all the way to rupture of the fibers is of little concern in a composite section represented by the combination of the deteriorated steel and FRP. The superposition of the steel's perfectly plastic behavior and the linearly elastic behavior of the FRP results in an apparently ductile behavior up to failure of the composite section. In plastic design of steel sections, this behavior is termed "constrained plastic flow." The behavior of the elastic FRP on the extreme fiber of the steel is very like the plastification of a wholly steel section with the plastic flanges restrained by the elastic core of the web. In the case of the FRP-rehabilitated steel section, the elastic FRP restrains the plastic steel core. The resultant behavior resembles strain hardening of a wholly steel section.

## MATERIAL SELECTION CRITERIA/ ENGINEERING PROPERTIES

In attempting to recover some of the lost resistance of the steel components, comparable strength is desired. Because of this, carbon fiber reinforced polymers (CFRPs) are the logical choice for strengthening deteriorated steel components. The costs of CFRPs are significantly greater than those of glass fiber reinforced polymers (GFRPs), but, as previously discussed, the material cost of this application is not the most significant component of the total cost.

## FABRICATION/CONSTRUCTION

There are two different types of FRP rehabilitation. The simplest and most common type involves adhesively bonding prefabricated FRP plates or strips (e.g., pultruded strips) onto the prepared deteriorated steel surface. For more complicated geometries (e.g., three-dimensional joins such as floorbeam-to-girder connections), a fabric of fibers may be placed against the prepared deteriorated steel surface and the FRP made in place by coating the fabric and the adjacent steel surface with resin. For both types of rehabilitation, if CFRPs are used, the steel must be sufficiently isolated from the carbon to prevent cathodic interaction; this has been ensured through the introduction of a glass scrim between the carbon and the steel. Further, for both types of rehabilitation, the retrofit must be cured, either the adhesive bond or the resin itself.

Minimizing the time that a bridge must be closed to traffic is of utmost importance. There are promising developments in the effort to accelerate the cure time through elevated temperature. The possibility of curing a retrofit without disrupting traffic in lanes adjacent to the rehabilitation project should be investigated.

## COST-EFFECTIVENESS

The cost-effectiveness of the proposed rehabilitation of deteriorated steel components with FRP composite materials is due to the durability of FRP and savings in construction time, which decreases delays to the traveling public. Currently, two traditional rehabilitation options exist for deteriorated steel (i.e., steel that has been corroded, cracked, or deformed by collision). The damage can be plated over with a bolted retrofit, or the damaged area can be plated over or burned out and replaced with a welded retrofit.

In the case of the bolted retrofit, a bolted splice plate to be applied in the field will most likely be fabricated with holes in the shop. The fabricated plate will be taken to the field and used on the prepared deteriorated steel surface as a template to field drill the holes in the damaged component. The relatively heavy steel plate must be held in place while the holes are made. It must subsequently be removed so that its surface and the comparable faying surface of the damaged steel can be cleaned of cutting oil. The cleaned plate is then repositioned, and the bolts are inserted and tightened. The heavy steel plate must be handled and positioned many times to complete the retrofit. Even if adhesive bonding were used for applying the steel retrofit plate, workers would still have to deal with the heavy weight of the steel plate, especially during curing of the adhesive bond.

Most highway-bridge owners prohibit field welding. Cracking from field-welded repairs is relatively commonplace; therefore, for a repair for which field welding is considered, an FRP retrofit may prove more cost-effective and more durable.

## TRAINING

Training is required for bridge personnel to become more familiar with adhesive bond technologies. These personnel include designers, construction workers, inspectors, and maintenance personnel.

## METRICS FOR SUCCESS

Can the construction time and thus cost be ultimately reduced to the point where the increased initial higher cost of the FRP compared with traditional materials is recovered?

## INSPECTION AND MAINTENANCE

In the case of rehabilitation of steel components with conventional means, the inspection of the retrofit focuses on the joining method. Either the welds in a welded repair or the bolts in a bolted repair are inspected. This is also the case with FRP rehabilitation. The inspection of the retrofit on completion and the subsequent biennial inspection should concentrate on the interface bond between the deteriorated steel and the FRP composite material. Thermography can be used to ascertain the integrity of the adhesive bond between the FRP and the steel. Although this is a technology new to bridge infrastructure inspection, its introduction should be as easy as that of ultrasonic testing, radiography, or eddy-current for weld inspection.

The retrofit should require no maintenance other than occasional painting to match the steel, either painted steel or weathering steel. The painting is not required for durability, only for aesthetic reasons (i.e., to camouflage the retrofit).

## CONCLUSIONS

Widespread acceptance of repair and rehabilitation of deteriorated or damaged steel components with FRP composite materials looks very promising. The high initial costs of the relatively small amounts of FRP material needed for retrofit should be easily offset by reduced construction time and cost, which will subsequently reduce disruption to the traveling public. Further, innovation in rehabilitation is easier than in original design because reduced design lives are acceptable. Finally, bridge owners searching to extend the lives of older bridges will use materials that they may see as less proven than others and that they may be less willing to use for new construction.

# WHITE PAPER 3: FRP COMPOSITES FOR SEISMIC RETROFIT OF CONCRETE BRIDGES

## BACKGROUND

FRPs are used for seismic strengthening of reinforced-concrete structures when conventional strengthening techniques pose unacceptable problems to the designer or owner. In Europe and Japan, for example, one of the most popular techniques for upgrading concrete members has been to use externally epoxy-bonded steel plates. A similar approach has also been widely and successfully used in the United States for seismic strengthening of bridge columns. The use of steel plates is simple, cost-effective, and efficient. However, this technique also suffers from several disadvantages, including the difficulty of manipulating heavy steel plates and of welding at the jobsite and the need for scaffolding or lane closures for both of these activities. Other concerns are possible deterioration of the bond at the steel-concrete interface because of temperature differences or corrosion of the steel and the inability to visually examine the condition of the concrete in the core of the member following a major seismic event. Finally, for seismic response, the steel plate stiffens the member, causes a greater force to act on the structure, and may require retrofitting of members other than the one to which the steel plate is added.

Another technique for upgrading concrete structures has been to use reinforced concrete, shotcrete, or steel-fiber-reinforced jackets. While such jackets can be efficient in terms of strength and ductility, their construction is labor intensive, will usually require lane closures, and may also cause stiffening increases that are undesirable from the standpoint of seismic response.

## DESIGN REQUIREMENTS AND METHODS

Although FRP materials are highly deformable and can be bent around small radii, they are also relatively brittle. Their stress-strain characteristics remain essentially linear elastic up to failure, which occurs at relatively small strains. Because those failure strains can be less than the crushing strain of concrete, care must be taken in the use of FRP materials for seismic applications in which high ductility demands will be placed on the FRP-strengthened section.

Current design codes are, in effect, prescriptive limit-state design codes. Under seismic actions, forces and displacements can significantly exceed those associated with the elastic limit state; therefore, any plan to successfully implement FRP materials for seismic retrofit must be based on establishing through large-scale laboratory and field testing the actual failure limit state of retrofitted members. Through such testing, code provisions must be established that can accurately predict failure modes, failure loads, and failure displacements for the retrofitted system. In reinforced concrete, damage and failure mechanisms are directly dependent on reinforcement details and concrete properties (particularly those related to maximum aggregate size). Therefore, structural evaluation tests must be performed on specimens large enough to represent fully the complexities and behavior of the real materials and load transfer mechanisms existing in the field.

There is lack of agreement, nationally and internationally, on the specifications appropriate for the use of FRP with reinforced-concrete structures. Agreement on the approach appropriate for retrofit of concrete structures in general is needed; then, through careful consideration of the additional factors involved in seismic retrofit applications, the general approach should be extended to address these applications.

In addition, existing data on the durability of FRP need to be transformed into useful procedures for practical applications. There is a need for the development of standard tests to evaluate the durability of FRP materials. Finally, there is a need for robust durability models that can realistically predict the service life of both FRP materials and of the structural system with the FRP retrofit material attached.

Test methods need to be used that enable evaluation of FRP under stress and strain conditions reasonably equivalent to those that will be encountered by FRP on an actual structure. Special attention also needs to be given to specification and verification of the glass transition of the system (composite, resin, and adhesive as appropriate). Because the FRP composite on the structure will be subjected to wide changes in temperature, humidity, and moisture, verification that the specified glass transition temperature is always greater than the maximum ambient temperature that the FRP composite will experience is critical. The choice of the minimum specified transition temperature should include a factor of safety against the highest possible ambient temperature and also allow for the fact that incomplete cure can diminish the protection that the matrix provides to the fibers of the FRP composite.

Any plan for systematic evaluation of FRP for seismic retrofit should include durability testing of control samples conducted after intervals of exposure to field environments. Systematic evaluation should also include testing, after intervals of exposure to well-defined and controlled laboratory conditions, of the field-constructed FRP composites. The testing should include continuous measurements of stresses and strains at failure on coupons cut from the field and laboratory samples and measurement of the glass transition temperatures for the same samples. The field and laboratory conditions should duplicate the range of environments in which the FRP composites are likely to be used, and the field testing should cover a period of at least 2 years.

Considerable test information is now available on bridge structures seismically retrofitted with FRP. However, much of that information was developed to demonstrate that the retrofitted structures would perform satisfactorily under intense seismic actions. The test information should also be systematically examined to discover limitations to the current philosophies for the design of the retrofit.

## MATERIAL SELECTION CRITERIA/ ENGINEERING PROPERTIES

FRP materials always include two main components: fiber reinforcement and a polymer resin matrix. Secondary components are fillers used to enhance water resistance, weathering, dimensional stability, and so forth, as well as additives used to modify material properties and tailor the performance of the finished product. The performance and integrity of the fiber, the polymer resin matrix, and the concrete when encased by the fiber need to be evaluated for the range of long-term environmental conditions likely to be encountered in practice. It is necessary to evaluate the durability of the adhesives used to bond multiple fiber layers to one another and the fibers to the concrete. Likewise, it is necessary to evaluate the effectiveness of any additives that are included to resist the effects of long-term exposure to sunlight, increase fire resistance, add color, and so forth. Evaluation of matrix properties must verify glass transition temperatures, the ability of the matrix to protect the fiber in the environments to which the FRP composite will be exposed, and the overall compatibility of the fiber system used.

Most manufacturers and/or suppliers of FRP composite materials have performed durability testing of their systems at the product level. However, it is necessary to evaluate the corresponding performance of those materials over time when placed on concrete. In addition, for seismic applications, it is necessary to evaluate the ability of the FRP to perform as designed when the seismic action occurs many years after the FRP is installed. Further, because the products used in an FRP composite can be readily changed, systematic verification of strict adherence by the manufacturer to the use of products that have undergone rigorous evaluation is necessary.

It is widely accepted that FRPs, because of their unique physical properties, can be successfully used to improve the structural response of reinforced-concrete structures. However, FRP durability in the long run is still under investigation. FRP materials have been used for many years in the aerospace industry, and there have been extensive investigations related to the properties of these materials. However, their use in civil-engineering applications, particularly in seismic applications, exposes these materials to different environmental challenges than those encountered in aerospace applications. In addition, the quality control and manufacturing of FRP for aerospace applications usually differ significantly from the quality control and the fabrication procedures used for civil-engineering applications. Although studies related to the durability of FRP composite materials can be traced back to 1981, the vast majority of investigations related to FRP durability in civil-engineering applications have been carried out in the last 8 years.

The degradation of FRP materials can occur at the level of the fibers, the matrix, or the fiber-matrix interface. The sources of deterioration that have been more commonly studied are ultraviolet light, freeze-thaw conditions, moisture uptake, exposure to alkaline solutions, exposure to sea water, and temperature effects. The durability of FRP composites should be approached by considering the resistance of the individual components (i.e., epoxy and fibers) as well as the resistance of the combined components to certain environmental conditions.

The degradation of FRP composites is usually related to moisture penetration into the epoxy resin. Moisture causes the matrix to lose stiffness and reduce the protection of the fibers. The ingress of moisture into the matrix is believed to occur through cracks, voids, and diffusion as well as through mechanisms such as capillary action along the longitudinal axis of the fibers and along the interface of the resin-fiber system. Some epoxies have higher absorption rates than others, but, in general, absorption increases with increasing temperature. Generally, epoxies with low moisture diffusion characteristics are expected to have a better long-term performance and should be the preferred alternative.

Some contradictory research results exist on the effect of freeze-thaw cycles on CFRPs. It is important to note that the general agreement among researchers is that CFRPs are less vulnerable to environmental exposure than GFRPs. However, results vary considerably, making the quantification of this difference a difficult task.

The glass transition temperature ($T_g$) is one of the most important physical properties of thermosetting epoxies. Above this temperature, the strength and stiffness of the resin start to decrease. It has been reported that increasing moisture contents can lead to lower transition temperatures, which translates into lower mechanical properties.

Even if a given FRP material is proven durable, there still are concerns about the environmental effects of the concrete-composite system. A very important issue that has received little attention in the literature is the moisture encapsulation in concrete covered with FRP materials. It is well known that diffusivity and permeability of the epoxy matrix found in FRP, when compared with the same parameters in concrete, are negligible for practical purposes. Therefore, it is expected that moisture will penetrate and accumulate in concrete covered with FRP just under the area where these materials are applied. High-moisture contents can be highly destructive to reinforced concrete (e.g., when coupled with freeze-thaw cycling).

In recent years, the freeze-thaw durability of concrete enclosed with FRP materials has received particular attention.

The vast majority of the research has been limited to small concrete cylinders, and only one project has been reported on large-scale specimens. In general, it has been found that if the FRP material and the concrete are frost resistant, freeze-thaw conditions are not a threat to the structural integrity of the system, even if the concrete is fully saturated.

Existing guidelines address the long-term durability of FRP materials by incorporating strength reduction factors and limiting maximum service stresses from sustained loads. In addition, the potential risk of creep rupture is considered. The current durability guidelines are very general and do not take into account all the known parameters that affect FRP.

The necessary characteristics of the FRP composite at the time of the design seismic event can be determined through a structural test program. However, because of the infrequency of the design seismic event, it is also essential to validate that at the time of the event the FRP will have the properties necessary to provide the strength and toughness characteristics it displayed in the original test program. Further, it is necessary to validate that the addition of FRP will not increase the rate at which the combined FRP-structure system degrades over the rate of degradation that would have occurred if FRP had not been applied to the structure. Both the FRP degradation and the possibility of increased FRP-structure system degradation are valid concerns. These concerns have led bridge engineers to favor CFRP over E-Glass FRP, in spite of the greater cost of the carbon. For the same reasons, the resistance and capacity reduction factors that should be applied to the specified material characteristics of the FRP for the various possible modes of failure of the system under load need to take into account the possible degradation characteristics of the FRP and the system.

## FABRICATION/CONSTRUCTION

For seismic applications, it is essential that the FRP composite is tight against the structure. The typical FRP strengthening methods used for shear enhancement or inadequate length lap splice enhancement are passive methods rather than active methods. The concrete must start to crack up and dilate before the composite can engage. Thus, the FRP composite must be tight against the full length of the surface being restrained. For that reason, some engineers specify that the fibers be pretensioned or the composite jacket post-construction injection grouted to ensure that the concrete is properly restrained.

## QA/QC

QA/QC issues remain a major deterrent to the greater use of FRP in infrastructure applications. There are three issues that need to be addressed: surface preparation, FRP composite application, and acceptance criteria for the finished product. There is a general consensus on surface preparation requirements. FRP products are often cheaper and easier to place on the infrastructure when they are laid up by hand. However, the environmental conditions under which the lay-up is made are more critical for FRP materials than for concrete, asphalt, and steel—materials with which the construction engineer is more familiar. Temperature and temperature gradients, humidity and humidity gradients, wind, direct sunlight, and so forth at the time of placement can affect the viscosity of the polymer and the adhesives, as well as the rate at which curing proceeds for wet lay-up systems. Thus, experience, even for a single FRP product, as to the range of conditions over which construction can be undertaken with reliability, may not be readily transferable from one part of the country to another. The recommended acceptable conditions for installation of FRP materials vary widely. Installation criteria need to be systematically validated through extensive field testing in widely varying geographical and environmental conditions for each FRP system that is approved for use with infrastructure seismic rehabilitation.

## COST-EFFECTIVENESS

FRP jackets and reinforcement may be cost-effective alternates to steel-plate and concrete jackets. FRP can be used to considerably increase strength and ductility without increasing stiffness. Therefore, the use of FRPs in seismic retrofit applications can help prevent the need to retrofit other parts of the structure. For example, the increase in stiffness resulting from the use of a steel jacket to retrofit a bridge column for shear can cause larger shear and flexural forces to be transmitted to the foundation of the column, also requiring its retrofit. The use of an FRP jacket may obviate the need for foundation retrofit.

Two other design considerations are important advantages for FRP. First, the FRP wrapping can be tailored to meet specific structural requirements by adjusting the fiber orientation in various directions. Second, because it is chemically inert, the FRP wrap can also provide protection against corrosion and stray electrical currents.

There are several negative characteristics of FRP that also need to be acknowledged. With the exception of GFRPs, the cost of FRP material is relatively high, especially if used in small quantities. Also, the long-term properties of GFRP can be sensitive to aging, and, depending on the type of FRP material, there are differing environmental effects caused by ultraviolet radiation, moisture absorption, and corrosion. Knowledge about the effectiveness of FRP for seismic strengthening is well developed. However, knowledge is markedly lacking on the minimum amount of FRP material needed for strengthening, and therefore knowledge is lacking as well on cost-effectiveness issues, the significance of the long-term properties of the FRP for seismic strengthening, and how best to perform QA/QC for FRP installation.

## INSPECTION AND MAINTENANCE

In order to resolve difficulties during construction and to perform inspection of completed work, it is necessary for there to be a consensus on acceptance criteria for completed work and on the effectiveness of differing methods for repair of defects. However, criteria differ. Further, it is reasonable to expect that what is acceptable for seismic rehabilitation applications, in which the FRP must be tight against the member if it is to be effective as a replacement for inadequate confining steel, may need to be more stringent than the criteria for non-seismic applications.

Typically, for verification that the as-installed system meets design requirements, at least two types of testing must be done. Modulus, strength, and ultimate elongation tests must be made on test coupons cut from hardened, two-layer samples laid up at the same time as the system. System thickness, fiber volume, and number of plies must be verified from small core samples taken from the actual installation. The number of samples to be required per work day, the number of tests required on those samples, and the procedures to be followed for retest if the samples fail to meet specification must be defined. Again, the testing criteria required for seismic applications may reasonably be expected to be more comprehensive and extensive than for non-seismic applications.

## CONCLUSION

The issues that overwhelmingly predominate for the formulation of a performance-based strategic plan for the use of FRP material for seismic retrofit are (1) the degree of structural strength and/or ductility enhancement that can be provided by various FRP systems; (2) the durability of those systems; and (3) the ability to adequately address QA/QC issues. The latter issues include both the ability of the installers to meet design standards under varying jobsite conditions and the owner's ability to determine that those design standards have been satisfactorily met using consensus acceptance criteria.

# WHITE PAPER 4: FRP COMPOSITES AS BRIDGE DECKS AND SLAB SUPERSTRUCTURES

## BACKGROUND

Applying FRP materials to bridge decks or slab superstructures (i.e., decks spanning substructures without additional supports like girders) uses both of the significant attributes of FRP composites: light weight (with relatively high strength) and durability. Bridge decks constitute a relatively high percentage of the dead load of a bridge. The lighter weight of FRP bridge decks in comparison with a common cast-in-place or precast reinforced-concrete deck can be used to advantage in design of the supporting components and during construction. Unfortunately, the large mass of the bridge being replaced with FRP also constitutes a significant initial cost increase because of the relatively high initial cost of FRP in comparison with concrete. Many FRP replacement-deck technologies are related to patented manufacturing processes; these can cause procurement difficulties because of state and federal acquisition regulations.

## DESIGN REQUIREMENTS

Originally, bridge decks performed the simple function of providing a roadway for the traveling public and distributing the wheel loads to the supporting components. As bridge design evolved, in the more common case of decks on girders, the bridge deck was asked to perform the double duty of distributing the loads and acting compositely with the supporting components. The fact that traditional reinforced-concrete bridge decks act compositely with their supporting components, typically steel or prestressed concrete girders, makes the substitution of an FRP composite deck questionable in common cases.

The additional resistance that a reinforced-concrete deck adds to a composite girder cannot be matched by an FRP composite material deck using current technology or technology that will be available in the foreseeable future. Because of the linear-elastic nature of FRP composite materials, the force in the FRP deck is not as significant as that of a reinforced-concrete deck when the supporting girders are at ultimate resistance. Thus, the resistance of a composite-steel or prestressed-concrete girder with an FRP deck is not as great as that of a similar composite girder with a conventional reinforced-concrete deck. More importantly, the reduced dead load of the FRP deck does not fully compensate for the loss in resistance of the composite section. In other words, the steel or prestressed-concrete girder needed to support an FRP deck composite with the girder would be larger than the girder required to support a comparable reinforced-concrete deck.

For rehabilitation, this means that an FRP deck cannot replace a reinforced-concrete deck that is composite with the supporting girders. The substitution of an FRP deck can only be made on a girder bridge designed as a non-composite bridge. For new construction, in which composite construction is almost universal, this means that the girder supporting an FRP deck must be larger than one supporting a comparable reinforced-concrete deck to achieve the same resistance.

Even if this fact does not dissuade bridge designers, a satisfactory means of achieving composite behavior between the FRP deck and the supporting component must be developed. At times, the costs of making the deck composite (e.g., the cost of fabricating pockets to receive traditional shear studs) are comparable to the costs of fabricating the deck itself.

For the appropriate use of FRP composite material bridge decks, the load-distribution characteristics of the decks must be understood. Traditional reinforced-concrete bridge decks are relatively isotropic in stiffness. Bridge decks made of FRP composite materials can be designed as isotropic, orthotropic or perhaps even with a random stiffness orientation, as the bridge designer may orient the fibers as he or she chooses. Thus, the load-distribution equations for girders supporting decks (in fact, isotropic decks) from the AASHTO specifications are not necessarily valid for these decks.

Finally, bridge decks made of FRP composite materials are typically more flexible than traditional reinforced-concrete decks, much like orthotropic steel decks. Also, the surfaces of FRP bridge decks are too smooth, lacking in sufficient traction, and too fragile to remain unsurfaced. The relative flexibility can result in a strain incompatibility at the interface between the deck and the wearing surface, causing unbonding. Many bridge owners believe that this problem has yet to be adequately solved for steel orthotropic decks, and this also may be the case with FRP decks.

## DESIGN METHODS

The design of FRP composite material bridge decks is currently being treated like the design of bridge appurtenances: the design is left to the vendor. This practice is proving to be unacceptable. Bridge designers must become active in the process. The bridge-deck vendors can provide assistance, but the designer is ultimately responsible for the safety of the traveling public and ultimately, the successful performance of the deck over its service life.

## MATERIAL SELECTION CRITERIA/ ENGINEERING PROPERTIES

As bridge decks constitute a large mass, the cost of fabricating a bridge deck completely of carbon fibers is prohibitively costly. That being the case, without a gross change in production economies, FRP bridge decks will be made entirely of glass fibers or a hybrid using mostly glass fibers with selected carbon fibers.

## FABRICATION

FRP composite material bridge decks can provide adequate performance for the service life of the bridge if properly designed and fabricated. Unfortunately, recent FRP deck serviceability problems have arisen in the form of prematurely occurring cracks. Some have condemned FRP bridge decks as appropriate only for highways with limited traffic volumes. This need not be the case, but designers, fabricators, and owners must recognize the need for quality.

QA/QC is of utmost importance. FRP bridge decks must not be purchased as mass-produced commodities as if they were bridge appurtenances; they should be purchased as designed components such as fabricated steel or prestressed concrete girders. Inspectors should be present during the fabrication to ascertain the correctness of fabrication procedures and materials. The decks and their fiber orientations must be designed much as steel-plate girders, prestressed concrete girders, or steel-grid decks.

Ultimately, the design and fabrication of FRP decks may be quite similar to the current practices for prestressed concrete girders. Prestressed concrete girders are designed by a registered professional engineer—sometimes completely, other times conceptually, depending on an owner's requirements. If only conceptually designed, the fabricator develops the reinforcing scheme, the number of tendons, and their positioning to meet the conceptual requirements. A similar relationship between designer and fabricator may exist ultimately for FRP bridge decks.

## COST-EFFECTIVENESS

It is difficult to imagine that the initial cost of an FRP composite material bridge deck will ultimately be competitive with a simple reinforced-concrete deck. For FRP decks to be considered cost-effective for typical bridges, life-cycle costs must be considered. Other, special applications of FRP to bridge decks may be cost-effective when considering only initial costs. These applications include moveable bridges, for which counterbalance requirements could be greatly reduced, and rehabilitation of load-restricted non-composite bridges, including trusses. For non-composite applications, the reduction in dead load can have a significant effect on load-carrying capacity.

## TRAINING

Significant training is required for all phases in the use of FRP bridge decks. Designers and fabricators of FRP bridge decks must learn the ways of the bridge-engineering community. Bridge designers, erectors, inspectors, and maintenance personnel must become familiar with the correct manner for dealing with and handling FRP composite materials.

## METRICS FOR SUCCESS

The metrics to measure the potential of success of this application are quite simple. They can be summarized in the following ways:

- Are FRP composite material bridge decks more durable and lighter than other alternatives that have similar costs? Or
- Are FRP composite material bridge decks so much more durable and lighter than alternatives as to warrant higher costs?

If the answer to either question is yes, the life cycle cost of FRP decks will be lower than alternatives.

## INSPECTION AND MAINTENANCE

One of the greatest needs in terms of the successful widespread application of FRP composite material bridge decks is in the area of inspection and maintenance. Simple, reliable methods are required for inspecting bridge decks before they are put into service and during biennial checks. Further, if damage or deterioration is discovered in service, simple and reliable repair procedures must be available. Similarly, defects occurring during fabrication must be easily detectable and repairable much as weld defects are repaired before accepting and installing traditional welded steel components.

## CONCLUSION

Widespread use of FRP composite material bridge decks as a substitute for reinforced-concrete bridge decks seems unlikely. The initial cost of a typical reinforced-concrete deck is relatively low. The typical source of reinforced-concrete deck deterioration is corrosion of the steel reinforcement. Enhancement to the corrosion resistance of reinforced-concrete decks through new and improved reinforcement (using new materials and enhanced conventional ones) should improve the life-cycle costs of these reinforced-concrete decks. It is difficult to imagine that FRP bridge decks will be cost-effective even when life-cycle costs are considered. Further, because of recent in-service problems, the durability of FRP decks in terms of serviceability cracking has been questioned for high-traffic volume routes. Although it is believed that quality control can alleviate these problems, the question of the cost-effectiveness of FRP decks remains.

# WHITE PAPER 5: FRP COMPOSITES AS INTERNAL REINFORCEMENT OF CONCRETE COMPONENTS

## BACKGROUND

Structural concrete components, either reinforced with mild steel reinforcement or prestressing tendons, have proven to be less durable than originally expected. When subject to de-icing agents or naturally occurring salt-laden water, traditional metallic reinforcement corrodes as these liquids permeate the concrete. The corrosion has two effects: (1) the metallic reinforcement loses resistance as its effective cross-sectional area decreases, and (2) concrete surrounding near-surface metallic reinforcement cracks and spalls as the volume of the metal and its corrosion products grows. More recently, inadequately grouted post-tensioning tendons have been subject to debilitating corrosion. Replacing the corrosion-sensitive metallic reinforcement with less corrosive materials is a sound strategy. FRP composite material manufacturers, noting the relatively short service lives of traditionally reinforced-concrete bridge decks and the large square footage of existing and deteriorating decks, realized that there was a high potential for the successful application of FRP composite materials.

FRP composite materials can have two distinct advantages over traditional construction materials: (1) they have the potential to be more durable, and (2) they are lighter in weight. The application of FRP composite materials for internal reinforcement of concrete components uses the potential for increased durability; in this case, non-corrosive reinforcement will not cause spalling of concrete. The potential for successful use of FRP as external reinforcement also exists. The lighter weight of FRP materials in comparison with traditional materials is not an advantage in this application because the percentage of reinforcement relative to the mass of concrete is almost insignificant. Unfortunately, the increased initial cost of FRP internal reinforcement may be a disadvantage as enhanced traditional-material applications with lower life-cycle costs are developed.

Designers looking further into the future warn of the foolhardiness of merely replacing one material with another. They suggest that the components should be redesigned to better use the new material's enhanced attributes. This may be the case for internal reinforcement of concrete components with FRP composite materials.

## DESIGN REQUIREMENTS

The application of FRP composite materials as internal reinforcement of concrete components is perhaps the most advanced application of FRPs to highway structures. Much academic research has been done, and design and material specifications in fields other than highway structures exist. For application of FRP composite materials as internal reinforcement of concrete components to be successful, the issue of developing and anchoring the reinforcement must be addressed. In general, FRP reinforcement and tendons are not as easily developed and anchored as traditional steel reinforcement and tendons.

Development length provisions have been developed for FRP composite material reinforcement. The provisions are, in general, more severe than those for uncoated black bars. Alternative reinforcement configurations are even being suggested, such as reinforcement in the form of a grid, like grid-reinforced-concrete decks (the newly espoused industry name for fully and partially filled steel-grid decks). Grid-based reinforcement has an additional mechanical bond between the grid and the concrete, providing excellent development. Such a grid-based system is compatible with the premanufactured (as opposed to built-on-site) nature of FRP applications.

Anchorage of prestressing tendons, which is traditionally accomplished through teethed wedges, is a challenge for FRP composite materials in which the resistance to the "biting" of the teeth is less than for steel. Nonetheless, innovative anchorages are being developed. The anchorage of FRP tendons is a challenge, but it is not unachievable.

## DESIGN METHODS

Traditionally, structural concrete is designed to be under-reinforced. In an under-reinforced concrete section, as the ultimate load-carrying capacity is approached, the metallic reinforcement yields before the crushing of the concrete in compression. This desirable behavior results in a gentle, ductile failure, giving the users of the structure warning of impending failure through large deformations before failure. The stress-strain curve of construction steel with a linear elastic region followed by a perfectly plastic region and with the relatively brittle behavior of concrete works to yield a ductile composite material when used in the proper proportions.

Replacing the steel reinforcement with FRP composite materials results in a far-reaching change of behavior. As the FRP composite material reinforcement has a linear stress-strain relationship up to a sudden rupture-type failure, the concept of under-reinforced sections must be revisited. In effect, the goal of the design of an under-reinforced section is to preclude sudden failure by crushing of the concrete. Designers of FRP composite material reinforcement and the specification writers have approached this in a different manner. Rather than providing ductility to preclude crushing of the concrete, they provide sufficient reserve strength to preclude crushing. Technically, this alternative design concept is adequate if the various uncertainties are properly assessed and the appropriate resistance factors are developed. For the concept to be embraced by engineers, they will have to become more familiar with FRP composite materials and their behaviors. Finally, because FRP is not bent in the same manner as traditional steel rebar, the appropriate shaping of FRP bars (and reshaping in the field, as needed) requires considerable thought.

## MATERIAL SELECTION CRITERIA/ ENGINEERING PROPERTIES

The choice of material for internal reinforcement of concrete is not a critical issue. For example, in traditional reinforced-concrete components with mild reinforcement, the grade of steel used is one of the lowest qualities of steel used in construction. Strength is the issue; toughness is not. FRP composite materials can easily meet the required properties.

## COST-EFFECTIVENESS

The existing problems with the durability of reinforced-concrete bridge decks and the large square footage of existing and planned bridge decks are spawning many potential solutions to the corrosion problems associated with uncoated “black” steel reinforcing bars. In addition to FRP composite material reinforcement, epoxy-coated, stainless-steel-clad, solid-stainless-steel, and new formulations of mild steel (i.e., MMFX) reinforcing bars are being proposed as more durable alternatives. Reinforced-concrete decks reinforced with smaller percentages of steel (i.e., the LRFD empirical deck design) or even no internal reinforcement at all (based on the theory of internal arching action, not bending) are being used to diminish the potential for corrosion of traditional steel reinforcement. These alternatives, which use more familiar metallic materials, are much less costly than alternatives using FRP composite materials.

These more easily implemented alternatives are being aggressively marketed, and the number of FRP-reinforcement projects funded through FHWA’s IBRC program are in decline as projects using the new metallic-based reinforcements are growing. This suggests that states are more amenable to the more traditional materials. However, this may reflect cultural considerations more than technical ones. Unfortunately, the lighter weight of the FRP composite materials is not an advantage in this application. Thus, the increased durability of FRP must fully compensate for its higher cost for it to be cost-effective.

## TRAINING

Training requirements for this application of FRP are minimal. Because the reinforcement in a concrete beam is relatively one-dimensional in nature, proportioning reinforcement of steel or FRP is relatively similar. The only differences are the design methodology differences discussed above. Construction personnel familiar with the placement of traditional steel reinforcement can easily be trained to handle the requirements of placing FRP reinforcement.

## METRICS FOR SUCCESS

The metrics to measure the potential for success of this application are quite simple. They can be summarized in a simple question: Are FRP composite material reinforcements sufficiently more durable (i.e., much less corrosive) than the newly introduced enhanced-property traditional metallic reinforcements to warrant their additional initial costs?

## INSPECTION AND MAINTENANCE

Inspection and maintenance of existing bridge decks is focused overwhelmingly on the quality of the concrete; even measurements of corrosion in steel reinforcement relate more to the spalling and cracking of concrete than to the loss of reinforcement section and thereby strength. Because of this focus, little if anything must be changed to accommodate inspection and maintenance of FRP-reinforced concrete decks. In fact, with less potential for corrosion, the various methods of detecting or predicting active corrosion of the steel are no longer required.

## CONCLUSION

Using FRP composite material reinforcement in concrete components is the most promising application for FRPs in the highway infrastructure in terms of the technology being ready for implementation. Unfortunately, advances in the enhancement of traditional metallic reinforcement bring into question the cost-effectiveness of the FRP application.

Bridge engineers look at the problem of corrosion of internal reinforcement differently depending on whether the reinforcement is non-prestressed or prestressed. In the case of internal non-prestressed reinforcement, engineers are looking for an alternative to black rebars. The prospect of FRP rebars replacing black bars is looking less likely as bridge engineers are exploring alternative traditional materials, which are much cheaper than FRP rebars in today’s marketplace. These alternative traditional materials include black bars with enhanced corrosion resistance and solid-stainless, stainless-clad, and galvanized rebars.

In the case of the corrosion of post-tensioned steel tendons, a current cause of concern, bridge engineers are less concerned with the potential corrosion susceptibility of the tendons than with the inadequate protection provided by improper grouting. They look not so much for alternative tendons as to alternative means to place and inspect the grout.

# APPENDIX E

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Abbreviations used without definitions in TRB publications:

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| 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 |