NCHRP

REPORT 564

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Field Inspection of In-Service FRP Bridge Decks

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## DETAILS

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# Field Inspection of In-Service FRP Bridge Decks

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Niket M. Telang at CTL was the original principal investigator for this project; Adrian Ciolko of CTL led the project through completion of outstanding tasks commencing in July 2004. Armin Mehrabi (formerly of CTL), Project Consultant from Bridge Engineering Solutions, Inc., and Chris Dumlao of Dumlao Consulting, Inc., were members of the research team.

# FOREWORD

By David B. Beal
Staff Officer
Transportation Research Board

This report contains a manual for the in-service inspection of fiber reinforced polymer (FRP) bridge decks. Documentation of the research leading to the development of the inspection manual is also included. The material in this report will be of immediate interest to FRP bridge inspectors, designers, and owners.

Inspection and monitoring of FRP structures varies widely, from no monitoring, to visual inspection, to experimental nondestructive evaluation techniques. The criteria for field inspection should be based on identification of critical components of FRP decks and determination of critical accumulated damage thresholds in those components. Other inspection issues include accuracy and reliability requirements for inspection data, continuous versus periodic data collection, depth and frequency of inspection, reliability requirements for equipment and sensors, and calibration of the guidelines with field project data.

In addition, the type of inspection data collected and the recording format vary. As a consequence, it is difficult to compare one project with another. Thus, there is a need for a standard inspection reporting format to make such comparisons possible. Comparative data would also help the composites industry to refine the technology to better meet the states' needs.

The objective of this research was to develop recommended field procedures, evaluation guidelines, and reporting standards for periodic inspection of in-service FRP bridge decks. This material has been assembled into a detailed inspection manual covering all aspects of FRP deck inspection. A report documenting the research effort leading to the development of the manual is bound with the manual, and extensive appendices to the report are available on the NCHRP website. An instructor's guide, composed of a series of PowerPoint slides suitable for use in an in-house training program in the application of the inspection manual, is available from NCHRP.

This research was performed at the Construction Technology Laboratories, Inc., with the assistance of Dumlao Consulting, Inc.; Bridge Engineering Solutions, Inc.; and California Maritime Academy.

# CONTENTS

## PART I INSPECTION MANUAL

## PART II REPORT

# PART I:

## INSPECTION MANUAL

# SUMMARY: INSPECTION MANUAL

After the Cold War, the technology transfer initiatives taken by the federal government to use the unused manufacturing capacities of composite manufacturers in the military and space industries resulted in the proliferation of fiber reinforced polymers (FRP) usage in the bridge industry. Some of these companies capitalized on the potential of the transportation market and were instrumental in advancement of FRP use on bridge structures. Since the 1990s, numerous bridges with FRP decks have been built in the United States, and the number of such bridges is continuously growing as bridge engineers become comfortable with the material and its performance. However, most of these bridge decks have been built using proprietary experimental systems and details. The lack of standardization has been a challenge to bridge engineers, who traditionally are accustomed to standard shapes, sizes, and material properties. In addition, variations in the design and composition of FRP decks have resulted in unique problems and maintenance issues associated with each type, thereby complicating the upkeep of these decks.

As the usage of FRP decks becomes more widespread, the state DOTs will need to have guidelines and uniform standards to inspect, assess, and evaluate the condition of their in-service FRP deck bridges in order to maintain public safety.

The goal of this manual is to recommend uniform guidelines for inspection and condition evaluation of in-service FRP bridge decks. These guidelines could be adopted by DOTs and AASHTO at the state and national levels. The manual is based on current knowledge on FRP material and decks, ongoing research, experiences gained from state DOTs' experimental FRP deck projects, experience of the defense and aerospace industries, and present practice in assessing this material in the United States and abroad. The manual targets the practicing engineer and bridge inspector, and its content and organization is designed to supplement the existing FHWA bridge inspection manuals and courses.

# SECTION 1: INTRODUCTION

## 1.1 PURPOSE OF THE MANUAL

This manual presents guidance for inspection and assessment of in-service fiber reinforced polymer (FRP) bridge decks. Currently, there are no generally accepted uniform standards or guidelines for field inspection of in-service FRP bridge decks. As the use of FRP decks becomes more widespread, state DOTs will need uniform standards to inspect and evaluate the condition of in-service FRP deck bridges. This manual develops a uniform approach for inspection and evaluation of in-service FRP decks.

The manual is based on the findings of research sponsored by NCHRP. The objective of the NCHRP Project 10-64, Field Inspection of In-Service FRP Bridge Decks, is to develop a manual and an inspector's training course for field inspection of in-service FRP bridges. The research is based on current knowledge of FRP material and decks, ongoing research, experiences from experimental FRP deck projects, experiences of the defense and aerospace industries, and the present practice in the use and assessment of this material in the United States and abroad. The manual and course target the practicing engineer and bridge inspector, and their content and organization are designed to supplement existing FHWA bridge inspection manuals and courses.

## 1.2 APPLICABILITY OF MANUAL

This manual is intended as a comprehensive document for use in field inspections of in-service FRP decks. It is focused only on the inspection of FRP decks and, as such, does not address other aspects of bridge inspection covered in other publications by FHWA and AASHTO. Therefore, this manual shall be used in conjunction with other AASHTO, FHWA, and NCHRP references and manuals that cover complementary subjects of bridge inspection.

These other complementary manuals and reference materials include, but are not limited to, the latest editions of *National Bridge Inspection Standards* published by the federal government; *Standard Specifications for Highway Bridges* and *The Manual for Condition Evaluation of Bridges* published by AASHTO; *The Safety Inspection of In-Service Bridges—Participant Notebook, Bridge Inspector's Training Manual*, and *Recording and Coding Guide for Structure Inventory and Appraisal of Nation's Bridges* published by FHWA. In addition, specific codes and specifications published by state DOTs or other local governing authorities shall also be used in conjunction with this manual. Issues related to all bridges and bridge components other than FRP decks shall be addressed in accordance with all existing codes and standards including the publications listed above.

## 1.3 INTENDED USERS

This manual targets practicing bridge engineers and inspectors who inspect, assess, or evaluate FRP decks. The manual provides comprehensive information on FRP materials, compares them with conventional bridge materials, identifies specifics of various FRP deck configurations, highlights important elements and details of FRP decks and related components, identifies inspection and assessment methods for observed damage, and provides methods for correlating these assessments to uniform rating factors for use in assessing bridge elements.

## 1.4 BACKGROUND

Federal technology transfer initiatives taken after the Cold War to utilize composite manufacturing capacities no longer needed by the military and aerospace industries led to the proliferation of fiber reinforced polymers (FRP) use in the bridge industry. Some companies capitalized on the potential of the transportation market and helped advance the use of FRP on bridge structures. Since the 1990s, numerous bridges with FRP decks have been built in the United States, and the inventory of such bridges is growing as bridge engineers gain confidence in the material and its performance. However, most of these bridge decks have been built using proprietary experimental systems and details. The lack of standardization of shapes, materials, and composition has challenged bridge engineers accustomed to standard shapes, sizes, and material properties. In addition, variability in the design and composition of FRP decks has resulted in unique problems and maintenance issues associated with each type, making the upkeep of these decks a challenge to inspection and maintenance personnel.

As the use of FRP decks becomes more widespread, the state DOTs will need guidelines and uniform standards to inspect and evaluate the condition of their in-service FRP deck bridges in order to maintain public safety. This manual is based on research into the performance of FRP bridge decks from published literature; DOT reports; current inspection practice; military and aerospace manuals; and experiences of practicing engineers, researchers, and inspectors involved in the design, construction, inspection, or maintenance of FRP bridge decks. This information has been distilled, synthesized, and presented in this comprehensive manual.

## 1.5 MANUAL ORGANIZATION

The manual is organized into eight sections. The sections present an introduction to FRP materials, material composition and properties, FRP decks and installation practices, design and construction details, and inspection and assessment of FRP decks. The specific sections of the report are as follows:

**Section 1 – Introduction:** This section provides background information on FRP material and decks, the purpose of this manual, the goals accomplished through this manual, and the manual organization. In addition, this section provides guidance on how best to use this manual.

**Section 2 – FRP Material:** This section provides background on FRP material and its use in civil engineering, common material properties, standards and specifications commonly used for design and manufacture of FRP material, and the philosophy of FRP material design.

**Section 3 – FRP Decks and Installation Practice:** This section provides details on various types of FRP decks, comparative assessment of the various deck designs, installation practices, and FRP deck component details.

**Section 4 – Significant Deck Details and Damage Types:** This section discusses and illustrates the various details in FRP deck cross section, attached components, and installation details.

**Section 5 – Inspection:** This section presents guidelines on inspection of FRP decks—with details on inspection locations, inspection methods, depth of inspection, and inspection frequency—along with a discussion on cost estimates and expertise required for the various inspection methods.

**Section 6 – Recordkeeping:** This section provides guidelines for collection and recordkeeping of FRP deck properties and inspection data. The section elaborates on the type of data to be collected and recorded on the FRP deck material and cross section, deck condition, and notation of damage and deterioration. In addition, this section provides guidance on a standard system for noting and describing deterioration and damage.

**Section 7 – Condition Assessment:** This section provides guidance on correlating the observed damage or deterioration to severity levels and condition ratings. In addition, this section presents discussion on causal elements, likelihood of damage progression, and potential likelihood of failure.

**Section 8 – Case Study:** This section provides an FRP deck inspection case study of the Salem Avenue Bridge in Dayton, Ohio.

## 1.6 HOW TO USE THE MANUAL

This manual is intended for use by bridge owners as a guideline and training resource for inspecting, assessing, and documenting condition of these new bridge elements.

Because FRP design, fabrication, construction, and behavior are unusual, inspectors and inspector trainees are urged to familiarize themselves with the first four sections. These sections serve as the foundation for effective inspection. Because specific nomenclature is used for FRP components, inspectors should refer frequently to the glossary provided in the manual to avoid future inspection documentation errors.

This section introduces the manual and provides guidance in using the manual for inspection purposes. Section 2 of the manual introduces both seasoned inspectors and inspector trainees to FRP material and its general construction uses.

Section 3 provides detailed information on FRP bridge deck designs, illustrated with drawings and details of the various FRP deck systems in use today on bridges in the United States. This section defines types of FRP decks, lists key manufacturers, describes typical details and installation practices, and provides a general discussion of the detailing philosophy. Unlike the traditional deck construction materials and systems that have been in use for close to a century, new FRP materials and systems have proliferated rapidly in only the last 10 years. Many of the deck fabricators and developers are manufacturers with core business activities unrelated to bridge construction. Therefore, inspectors need to familiarize themselves with the features of FRP bridge decks and their connections and with unique details of deck components such as the parapets, curbs, and wearing surfaces. To conduct accurate inspections and condition ratings, inspectors must also become familiar with presently known defects and symptoms of deterioration in FRP decks. These are identified in detail in Section 4.

Primary guidance on inspection techniques and their documentation for FRP decks is offered in Sections 5 and 6, including details of various inspection methods and their adaptation in inspecting FRP decks. Inspectors also receive guidance and references to specialized test methods beyond the scope of conventional inspection protocols; these specialized methods are to be used when unexplained or unexpected damage to FRP decks is discovered or suspected. Inspectors must become familiar with the guidance provided on recording and filing inspection data. Checklists of items are offered, along with the type of data to be collected for the various kinds of decks.

Section 7 discusses the assessment and rating of deck conditions and provides guidance on correlating inspection observations to the severity of the damage and rating of the deck condition. This section is of greatest interest to the engineer or inspector charged with assessing and evaluating the condition of the FRP bridge decks based on observed field conditions.

Inspectors are urged to review a case study providing an example of typical FRP deck inspection in Section 8. Guidance on terminology is provided in the Glossary. An index of topics concludes the manual.

For the convenience of the reader, the following quick-reference table provides guidance to this manual at a glance.

# HOW TO USE THIS INSPECTION MANUAL

| **LOOKING FOR...?** | **GO TO MANUAL SECTION** |
|---|---|
| If you are **already familiar** with FRP material and deck types, manufacturers, and processes | ***Section 4*** |
| To **familiarize yourself** with FRP **material** | ***Section 2*** |
| To **familiarize yourself** with FRP deck **types, details and construction** | ***Section 3*** |
| To **familiarize yourself** with **fabrication and construction** details and components | ***Section 4*** |
| To familiarize yourself with common **terminology** | ***Glossary*** |
| To learn what **inspection methods** are available, their costs, and the scope of their application | ***Section 5*** |
| To learn **how to record and file** and to review a list of things to inspect | ***Section 6*** |
| To learn how to use the inspection results to **rate the condition of the deck** | ***Section 7*** |

# SECTION 2: FRP MATERIAL

## 2.1 HISTORICAL PERSPECTIVE

FRP composite materials consist of two or more distinct constituent materials with recognizable interfaces between them. The constituent materials are intentionally combined to “engineer” a desired set of properties in the composite material so that it can perform its functions optimally.

Composite materials have existed for centuries—for example, ancient Egyptian culture improved the strength of building bricks by using straw as reinforcement in clay. Similarly, reinforced concrete can be considered a composite material. However, the focus of this manual will be specifically on polymeric resin-based composites.

Polymer-based composites were not widely used until after World War II, when fiberglass reinforcements and thermosetting resins such as polyesters became commercially available and affordable. In the 1950s and 1960s, much of the development in composite structures took place in the aerospace and automotive industries where composites’ high stiffness-to-weight ratio and corrosion resistance were immediately beneficial despite the higher cost per pound for finished goods. As new manufacturing techniques were developed, the cost for composite goods dropped, and demand spilled into other industries such as boating, sporting goods, tanks, and pressure vessels. In the last 20 years, a construction component manufacturing industry has emerged with several commercial companies offering FRP composite deck systems as drop-in replacements for steel or concrete deck systems.

## 2.2 FRP AND ITS USE IN CIVIL APPLICATIONS

The large-scale use of FRP composites in civil applications has occurred mostly within the last 15 years. A 1995 report by the Great Lakes Composites Consortium and BIRL/Northwestern University identified areas in which FRP composites could play key roles in rebuilding and maintaining civil infrastructure because of the composites’ corrosion resistance and high strength. The report data were gathered by asking transportation agencies and civil engineering professionals to define requirements that could be addressed with composites. The report identified four areas that FRP composites would improve: (1) corrosion mitigation, (2) reinforcement of degraded bridge components, (3) seismic protection, and (4) low-cost erection/maintenance.

Recent papers discuss FHWA research programs specifically related to FRP applications in bridge construction, strengthening, or repair and describe the ensuing growth of FRP materials in civil applications. In a section on new bridge construction, these publications succinctly describe some of the bridge systems developed and installed in 44 Innovative

Bridge Research Program projects as of 2003. These are in addition to installations under separate federal agency programs such as DARPA (Department of Defense Advanced Research Projects Agency) and various state DOT–sponsored programs.

## 2.3 FRP MATERIAL

Basic constituent materials such as fiberglass and polyester resins are produced in the millions of pounds per year, thanks to the popularity of FRP materials in the piping, automobile, sports, and boating industries. Composites offer the same appeal to these industries as to the infrastructure market, namely

- Material characteristics:
    - High strength,
    - Serviceability in both tension and compression,
    - Light weight, and
    - Corrosion-resistant.
- Usability characteristics:
    - Flexible processing and manufacturing,
    - Good impact resistance,
    - Easier handling because of light weight,
    - Quick installation, and
    - Potentially lower maintenance and lower life-cycle costs.

Compared with conventional construction materials such as steel, concrete, and aluminum, composite materials also have disadvantages:

- Material cost of 3 to 4 times that of conventional materials,
- Lower stiffness than conventional construction materials, and
- Susceptibility to ultraviolet and environmental degradation.

However, with proper engineering and treatment, some of these weaknesses can be overcome. Many of these issues have already been addressed in other industries. In addition, researchers, manufacturers, and suppliers who have pioneered FRP use in bridge decks have also tried to alleviate the disadvantages of FRP materials.

### 2.3.1 Basic Constituent Components of the Laminate

At the macro level, FRP composite materials are composed of two primary components: a polymer matrix resin and fiber reinforcements. Additives and fillers that enhance particular characteristics of the system are a third component. However, the resin and fiber reinforcements drive the material-dependent characteristics of the deck. With few exceptions, composites are built up of stacked layers, or laminates, of FRP material. Hence, the finished material is commonly referred to as a composite laminate.

#### 2.3.1.1 Matrix Resin

The matrix is the component that creates volume and supports the fiber reinforcement. All current bridge-deck systems employ thermosetting polymers as the matrix. Thermosetting polymers are a class of polymers that are worked in a liquid state and then chemically reacted to form a cured, solid state. It is this two-phase characteristic that enables the consolidation of fiber reinforcement into the matrix during manufacturing. Other matrix materials include thermoplastic resins and ceramic-type materials, but these matrix materials are not being used currently in deck manufacturing; therefore, this discussion is limited to thermosetting resins.

The most popular thermosetting resins being used in industry are described below.

**1. Orthophthalic Polyesters**

These general-purpose resins are the least costly and are widely used throughout the industry. Appearance, handling properties, and cure characteristics are similar for all polyesters as well as for vinyl esters. Strength, moisture, and fatigue properties are slightly lower than those of Isophthalic polyester. Curing is accomplished by the addition of a “catalyst,” which initiates a cross-linking chain reaction that quickly solidifies the resin during manufacture. The reaction time varies with formulation and heat, but solidification (or gel time) can occur from a few minutes to several hours after mixing, depending on process temperatures.

**2. Isophthalic Polyesters**

Iso-polyesters were developed to obtain better corrosion resistance and moisture resistance than are offered by general-purpose ortho-polyesters. Consequently, iso-polyesters are widely used in the boating and underground tank industry. Offering better structural and environmental characteristics than ortho-polyesters while costing less than vinyl esters, iso-polyesters have become the preferred material for bridge decks and other civil applications.

**3. Vinyl Esters**

Vinyl ester resins evolved from epoxy and thus exhibit higher material strength and better corrosion and environmental resistance than do ortho- or iso-polyester resins. Because vinyl esters cost more than iso-polyesters, they are seldom used unless required by extreme environmental conditions.

## 4. Epoxies

Epoxies differ chemically from polyester resins and cure through a different reaction process. Epoxies can be formulated with an infinite variety of chemical structures; thus, the physical properties can be tuned to enhance specific material traits. Epoxy systems typically consist of two parts—the resin and a hardener—which are mixed, then allowed to cure. Physical properties of epoxies are highly dependent on curing temperature and are better for elevated temperature systems versus room temperature cure.

Epoxies are considerably more expensive than the polyesters or vinyl esters, so epoxies are generally used where peak performance is required, as in the aerospace industry. No manufacturers currently use epoxy resins for their bridge deck system.

Table 2.3.1.1-1 lists the mechanical properties of the polyester matrix resins without and with fiber reinforcements (fiberglass mat type). As seen in the table, the strength and stiffness of the composite material comes mainly from the fiber reinforcements. One must keep in mind that the resin serves to protect the fibers and provides a mechanism for load transfer between fibers. The heat deflection temperature (HDT) is the temperature at which the resin will "soften" and lose strength. Note the higher HDT temperature of vinyl ester over the polyesters.

**Table 2.3.1.1–1 Typical Mechanical Properties of Common Resins [1]**

| Resin System | | Compressive Strength ksi | Tensile Strength ksi | Tensile Modulus Msi | Heat Deflection Temp °F |
|---|---|---|---|---|---|
| Orthophthalic | Without reinforcement [2] | NA | 7.2–8.5 | 0.45–0.66 | 175 |
| | With fiberglass reinforcement [3] | NA | 22 | 1.7 | |
| Isophthalic | Without reinforcement [2] | 17 | 10–11.7 | 0.45–0.65 | 195 |
| | With fiberglass reinforcement [3] | 30 | 23 | 1.7 | |
| Vinyl ester | Without reinforcement [2] | NA | 11–12.7 | 0.46–0.57 | 212 |
| | With fiberglass reinforcement [3] | 30 | 23 | 1.6 | |
| Epoxy | Without reinforcement [4] | NA | 7–8 | 0.43–0.55 | 120–220[5] |
| | With fiberglass reinforcement [3,4] | 35 | 30 | 1.8 | |

[1] Hancox and Mayer, *Design Data for Reinforced Plastics*, Chapman and Hall, London, UK, 1994.
[2] Typical range after full cure, dry. Not normally used in structure without reinforcement.
[3] Based on fiberglass mat reinforcement at 40% fiber volume.
[4] Room temperature cure epoxy systems, heated systems will be slightly higher.
[5] Low value is for room temperature cure, high value for heated process.

### 2.3.1.2 Fiber Reinforcement

A variety of reinforcement fibers have been developed in the composites industry, but to date only a few—namely, E-glass fiberglass and high-strength carbon fibers—have made it to commercial use as commodities, mainly because of cost and broad availability. Table 2.3.1.2-1 compares the mechanical properties of these and other fibers, which may in the future see their way into deck construction.

**Table 2.3.1.2-1 Mechanical Properties of Reinforcement Fibers**

| Fiber Type | Density (lb/in$^3$) | Tensile Modulus ($10^6$ psi) | Tensile Strength (ksi) | Used in Bridge Deck? |
|---|---|---|---|---|
| **Glass** | | | | |
| E-glass (Vetrotex) | 0.091 | 11 | 492 | Yes |
| S-2 glass (OCF) | 0.09 | 12 | 653 | |
| **Aramid** | | | | |
| Kevlar 29 (du Pont) | 0.052 | 11 | 481 | |
| Kevlar 49 | 0.052 | 17 | 400 | |
| **Oriented polyethylene fiber** | | | | |
| Spectra 900 (Allied signal) | 0.035 | 17 | 384 | |
| **Carbon** | | | | |
| High strength/strain | .061–.069 | 23–36 | 203–715 | Yes |
| Intermediate modulus | .061–.069 | 40–46 | 339–1,025 | |
| High modulus | .063–.072 | 49–63 | 276–800 | |
| Ultra high modulus | .068–.072 | 64–120 | 270–500 | |
| **Alumina** | | | | |
| Safimax SD (ICI) | 0.119 | 44 | 290 | |
| **Alumina/boria/silica fiber** | | | | |
| Nextel 440 (3M) | 0.108 | 27 | 290 | |
| **Silicon carbide** | | | | |
| Sigma (BP Metal Comp.) | 0.123 | 57 | 508 | |

In their dry singular state, all reinforcing fibers are basically thin, high-strength strands bundled together to form a larger strand called a "roving," which is wound onto a spool for distribution (see Figure 2.3.1.2-1). Obviously, in this state the fibers take only tension forces as a rope does. They must be mixed with solidified resin to develop structural resistance outside of pure tension (i.e., compression and shear strength). (For details of how fiberglass and carbon fibers are manufactured, visit the website of any producer of fiberglass or carbon fibers.) After the fibers are spooled, they can be used as raw material for fabrication or be processed again into other forms, which are then used in manufacturing. The typical forms of reinforcement available to the manufacturer for fiberglass, carbon, or any other fiber materials are discussed below.

### 1. Continuous Roving

The lowest usable form of reinforcement is a bundle of strands, which may consist of hundreds of monofilament threads gathered to form a thicker strand called a "roving."

These are wound onto spools as continuous strands and may be directly used as structural reinforcement in processes such as filament winding and pultrusion. Components having only rovings aligned in one direction will have highly unidirectional mechanical properties.

**Figure 2.3.1.2-1 Spools of continuous fiberglass roving.**

### 2. Discontinuous Roving

Discontinuous roving, or chopped strand glass, may be chopped into very small lengths ($\frac{1}{2}$ in. to 2 in.) and used to fabricate parts using hand-spray methods (Figure 2.3.1.2-2). Spray-up is one of the cheapest and quickest methods for producing a part, but it also gives the lowest strength and stiffness. This form of reinforcement is most often used where low fiber volume and reduced mechanical properties are acceptable.

**Figure 2.3.1.2-2 Chopped strand glass.**

### 3. Woven Rovings

Woven roving is produced by weaving fiberglass rovings into a fabric. This yields a coarse reinforcement product used in hand lay-up and panel molding processes. Many weave patterns are available, such as the plain weave pattern shown in Figure 2.3.1.2-3 for both fiberglass and carbon fabric. The weave can be made with more strands in one direction than in the other to create highly orthotropic properties.

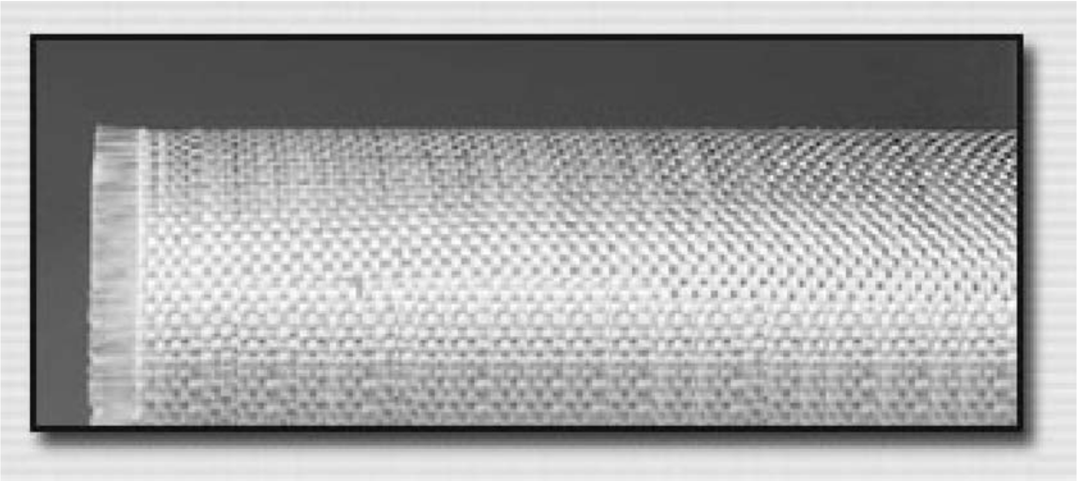


**Figure 2.3.1.2-3 Woven roving fabric.**

### 4. Mats

Mats may be produced as either continuous- or chopped-strand mats. A chopped-strand mat is produced by randomly depositing chopped strands onto a plate, then tacking them to each other using a small amount of binder. A continuous-strand mat is produced similarly, but without chopping. The resulting mat has better strength characteristics than a chopped mat. Figure 2.3.1.2-4 shows typical fabric rolls of mat.

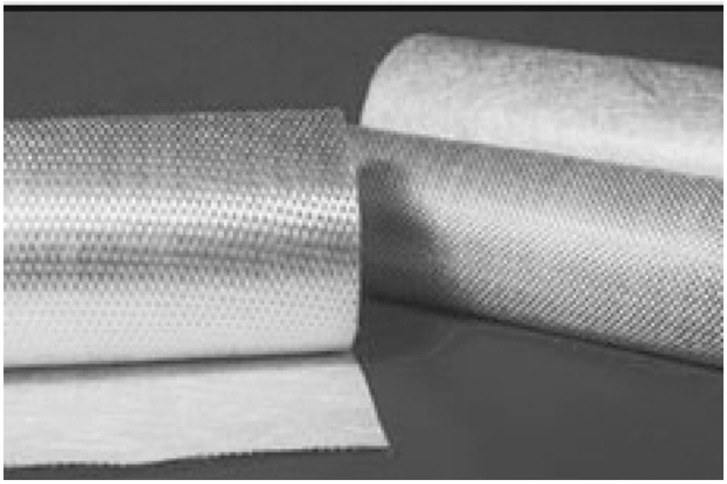


**Figure 2.3.1.2-4 Chopped strand mat fabric.**

### 5. Non-crimp Fabric

By stitching or knitting the reinforcement strands together using lightweight threads, sheets of fabric can be made without weaving to produce straight, non-crimped, layers of fibers (see Figure 2.3.1.2-5). This form of sheet reinforcement has become popular for deck fabrication because it allows large quantities of fiber reinforcement on single spools. Moreover, unlike woven fabric, the non-crimped fiber strands maintain their straightness and, hence, have higher stiffness and strength retention. Non-crimped fabrics are manufactured in multiple layers, so in essence they themselves are sub-laminates. On the other hand, however, non-crimp fabric costs more to manufacture than other forms.

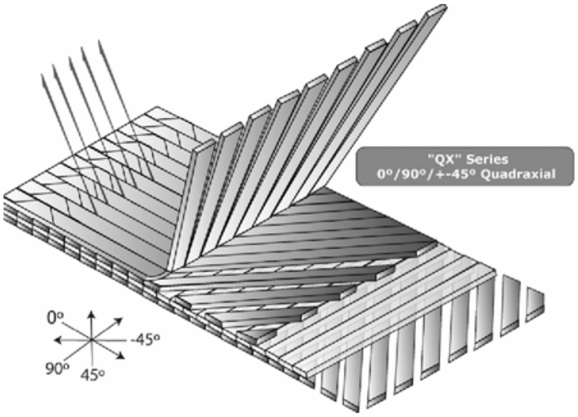


**Figure 2.3.1.2-5 Non-crimp fabric construction.**

### 2.3.1.3 Fillers

Fillers can be added to the matrix resin to alter, enhance, or control the material characteristics of the ensuing laminate. Manufacturers generally have a list and quantity of these fillers available for their products and, if needed, information on specific fillers used on a project can be obtained from the manufacturer. Table 2.3.1.3-1 lists some typical fillers and their function.

**Table 2.3.1.3-1 - Typical Filler Materials**

| Filler | Function |
|---|---|
| Aluminum trihydrate | Shrink reduction, flame retardancy, CTE reduction |
| Calcium carbonate | Resin thickener, UV stabilizer |
| Clay | Resin flow |
| Silica | Thixotropy |
| Glass spheres | Density reduction |

### 2.3.2 OTHER MATERIALS

In addition to the constituent materials, other materials may be introduced into the FRP material or added to the composite laminate as enhancements to improve specific properties of the FRP material. A short list and basic description of these components are given in the following sections.

#### 2.3.2.1 Adhesives

Adhesives are materials that join various substrates and laminates (also known as “adherends”) together. The total assembly of adhesive and adherends are known as joints. One of the major advantages of using adhesives is that it eliminates the drilling of holes or other mechanical methods for joining structural substrates. Examples of different types of adhesives include glue, hot-melt adhesives, pressure sensitive adhesives, film adhesives, and structural adhesives. These can be processed using various techniques including thermal, electron beam, ultraviolet (UV), and microwave curing. When using adhesives, cleanliness of substrates, silane coupling agents, and matching coefficients of thermal expansion (CTE) are all-important parameters for bond quality. Specialists with knowledge and experience in adhesive technology select appropriate adhesives based on the properties of the adherends as well as the likely environmental conditions to be experienced by the FRP component.

#### 2.3.2.2 Foam Cores

In some processes, such as in resin transfer molding, lightweight solid materials may need to be included in order to eliminate cavities and prevent resin pooling. Typical “core” materials are listed below in Table 2.3.2.2-1. Note that the type used by deck manufacturers may not be restricted to those mentioned.

These materials are also used to build the core section of sandwich type panels in some deck designs. Because all deck suppliers specify core material according to their design specifications, the list of materials is presented for reference only and provides a feel for the weight and expected sensitivity to water absorption of the material. Actual properties and environmental specifications must be obtained from the deck manufacturer.

**Table 2.3.2.2-1 Selected Light Weight Foam Cores**

| Material | Density (lb/ft$^3$) | Water Absorption (% estimate) | Relative Cost |
|---|---|---|---|
| Polyurethane foam | 5 – 30 | .2 | Medium |
| Urea-formaldehyde foam | 2 – 25 | 20 | Low |
| PVC foam | 5 – 30 | 15 | Low |
| Balsa wood | 2 –10 | Significant | Low |
| Honeycomb | 1 – 10 | Low | High |

#### 2.3.2.3 Gelcoat

Gelcoat is a thick resin overcoat applied to finished FRP components to improve either surface properties or surface finish, or both. The coating can be of a different resin than the matrix resin, one that is filled with UV inhibitors or fillers to improve surface toughness and weathering characteristics. Gelcoats are generally applied only to environmentally exposed surfaces such as at the sides or the bottom of the deck and not to the overlaid surface. The gelcoat is typically pigmented and is thus opaque, so it may mask laminate damages or blemishes that might be visible during manufacturing. Gelcoats can enhance the durability of the FRP composite by serving as a surface barrier against UV deterioration, flammability, and moisture pickup.

## 2.4 DISCUSSION ON STRUCTURAL FRP COMPONENTS

By combining the material constituents described above, designers can tailor their FRP composite. With the exception of rods and long narrow members, most FRP composites are composed of layers of fabric made with combinations of woven roving, mat, and non-crimp fabric saturated with resin then cured to obtain a solid structural laminate. This laminate, in turn, can be bonded to additional laminates to form the final structural member. This is best illustrated by the detailed lay-up specifications for the Schuyler Heim Bridge (Long Beach, CA) shown in Figures 2.4-1 and 2.4-2. The lay-up schedule contains more information than the reader requires to become familiar with FRP deck inspection, but the main idea of this illustration is to show the multitude of layers of FRP materials that define the overall cross section, including fiberglass fabric reinforcements (EQX), carbon reinforcements (C-LR), mat fabric (MAT), and secondary components such as a foam core and pre-made FRP pultruded tubes.

This particular deck shown in Figure 2.4-1 is a sandwich construction, so laminates are associated with particular sections of the deck as labeled in Figure 2.4-2. In general, most decks manufactured with FRP composites follow the same prescription for sandwich construction: namely, a lightweight core with load-carrying top and bottom facesheets. Information on other deck designs and fabrication techniques is included in Section 3.

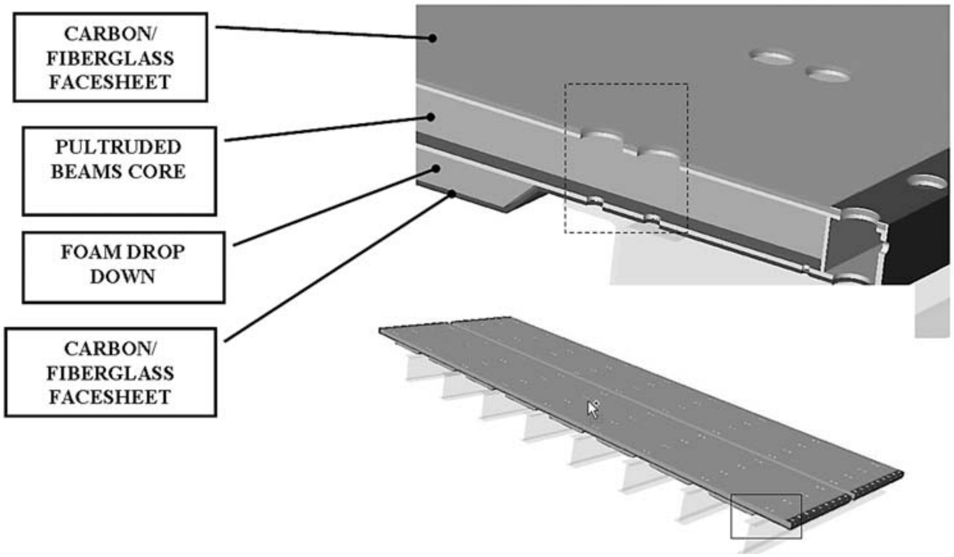
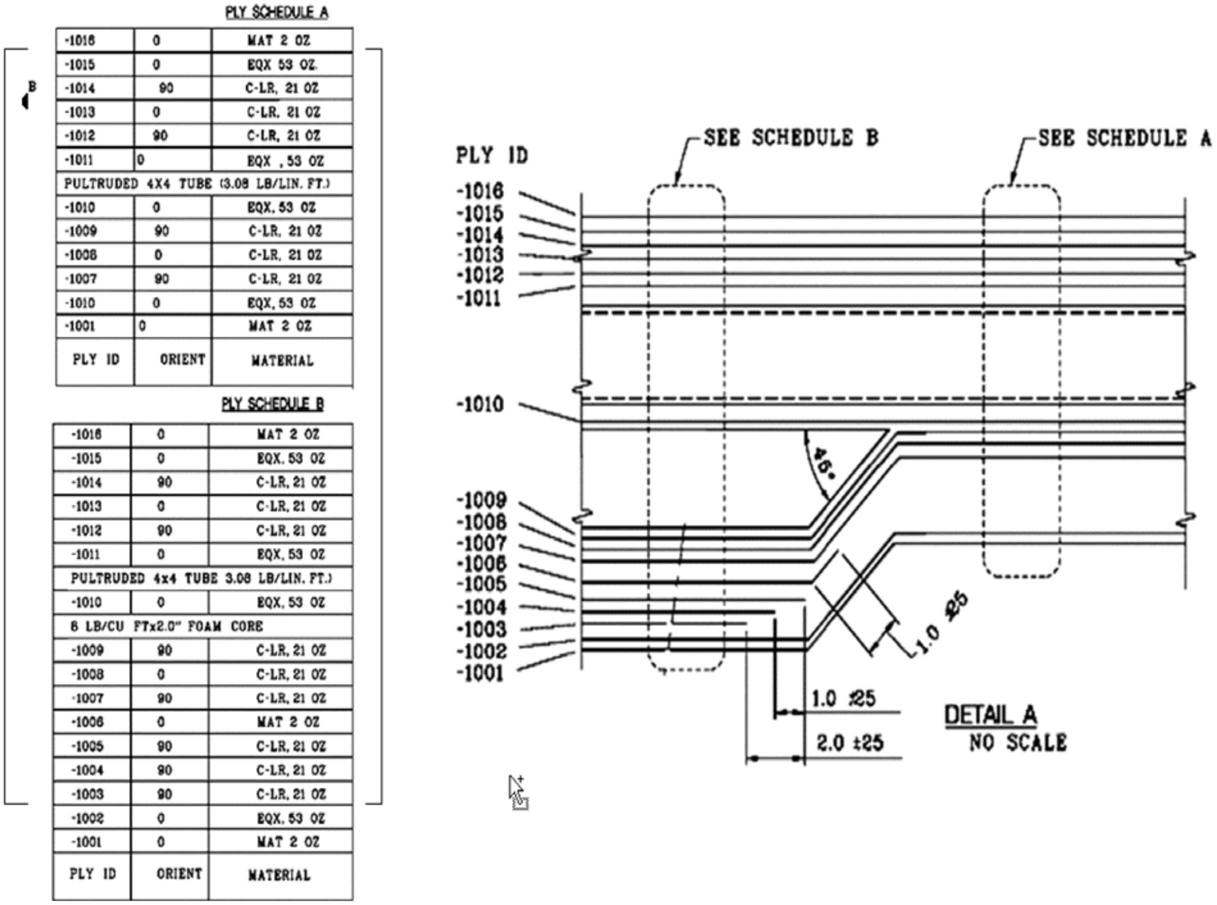


Figure 2.4-1 34-ft. x 6-ft. FRP composite deck for the Schuyler Heim Bridge.



PLY SCHEDULE A

| | | |
|---|---|---|
| -1016 | 0 | MAT 2 OZ |
| -1015 | 0 | EQX 53 OZ. |
| -1014 | 90 | C-LR, 21 OZ |
| -1013 | 0 | C-LR. 21 OZ |
| -1012 | 90 | C-LR, 21 OZ |
| -1011 | 0 | EQX , 53 OZ |
| PULTRUDED 4X4 TUBE (3.08 LB/LIN. FT.) | | |
| -1010 | 0 | EQX. 53 OZ |
| -1009 | 90 | C-LR, 21 OZ |
| -1008 | 0 | C-LR, 21 OZ |
| -1007 | 90 | C-LR, 21 OZ |
| -1010 | 0 | EQX, 53 OZ |
| -1001 | 0 | MAT 2 OZ |
| PLY ID | ORIENT | MATERIAL |

PLY SCHEDULE B

| | | |
|---|---|---|
| -1016 | 0 | MAT 2 OZ |
| -1015 | 0 | EQX. 53 OZ |
| -1014 | 90 | C-LR, 21 OZ |
| -1013 | 0 | C-LR, 21 OZ |
| -1012 | 90 | C-LR, 21 OZ |
| -1011 | 0 | EQX, 53 OZ |
| PULTRUDED 4x4 TUBE 3.08 LB/LIN. FT.) | | |
| -1010 | 0 | EQX, 53 OZ |
| 8 LB/CU FTx2.0" FOAM CORE | | |
| -1009 | 90 | C-LR, 21 OZ |
| -1008 | 0 | C-LR, 21 OZ |
| -1007 | 90 | C-LR, 21 OZ |
| -1006 | 0 | MAT 2 OZ |
| -1005 | 90 | C-LR, 21 OZ |
| -1004 | 90 | C-LR, 21 OZ |
| -1003 | 90 | C-LR, 21 OZ |
| -1002 | 0 | EQX. 53 OZ |
| -1001 | 0 | MAT 2 OZ |
| PLY ID | ORIENT | MATERIAL |

Figure 2.4-2 Laminate details for the Schuyler Heim Bridge deck.

# SECTION 3: FRP DECKS AND INSTALLATION PRACTICE

## 3.1 INTRODUCTION

Historically, composite materials—FRP in particular—have been used extensively in many areas, ranging from highly complex aerospace and military applications to more routine applications such as liquid storage tanks, fishing rods, and truck bedliners. Due to their low weight, high strength, and significant durability advantages, the most prevalent nonconsumer use of FRP material has been in the military aviation and civilian space applications. Although the defense and aerospace industry readily adopted composite materials in the 1960s, it took another 20 years before the bridge industry adopted them as viable alternatives to traditional materials.

FRP composite structures for use as vehicular bridge decks have successfully transitioned from the experimental to the commercial stage over the past decade. Nearly 100 FRP deck installations in the United States alone have thus far been cataloged by the composite industry's Market Development Alliance. The inventory of FRP deck placed in service clearly shows that small groups of manufacturers/suppliers have been successful at bringing FRP bridge decks to commercial viability. Manufacturing efficiency generally dictates the repeatable production of a standard design. Thus, despite the growing population of installed FRP decks, the actual number of unique deck designs can be reduced to the field of manufacturer/supplier sources (less than two dozen at present) and the number of deck types each has to offer.

## 3.2 DESIGN AND BEHAVIOR REQUIREMENTS

FRP composite bridge decks are required to meet the same design requirements as conventional bridge decks. Unless waived or modified by the bridge owner, typical design criteria are

- Live-load requirements per AASHTO H-20 or H-25 design loadings and
- Deflection criteria that typically require *L/d* ratio between 500 and 800.

The reader can obtain additional details and specific design requirements from project specifications issued by bridge owners.

## 3.3 TYPES OF FRP DECKS

Based on their composition, FRP decks can be divided into three categories: honeycomb sandwich, solid core sandwich, and hollow core sandwich.

### 3.3.1 TYPE 1: HONEYCOMB SANDWICH

This type of deck is shown in Figure 3.3.1-1. These FRP decks both use identical sine-wave web patterns in their cores as shown in the figure.

**Figure 3.3.1-1 Honeycomb sandwich configuration.**

This core construction provides considerable flexibility in tailored depth. However, the hand lay-up process now employed requires painstaking attention to quality control in the bonding of the top and bottom facesheets to the core.

### 3.3.2 TYPE 2: SOLID CORE SANDWICH

Solid core decks have foam or other fillers in the cores. They are generally manufactured using a process called VARTM (Vacuum-Assisted Resin-Transfer Molding; this process will be discussed in Section 3.5.2). The FRP decks shown in Figure 3.3.2-1 both use solid core sections.

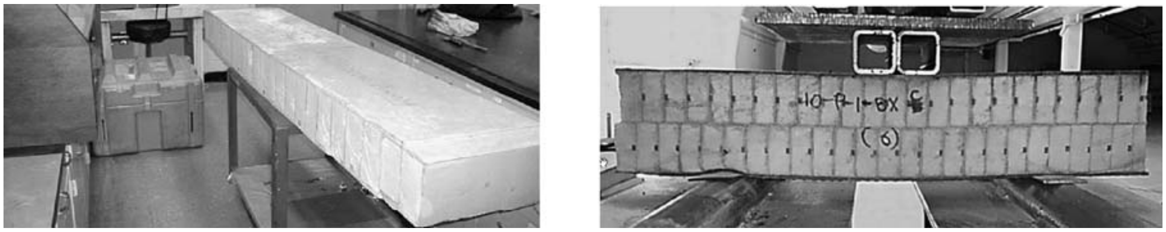


**Figure 3.3.2-1 Solid core sandwich configuration.**

### 3.3.3 TYPE 3: HOLLOW CORE SANDWICH

The third type of FRP deck consists of pultruded shapes fabricated together to form deck sections. These FRP decks typically have continuous hollow core patterns as shown in Figure 3.3.3-1.

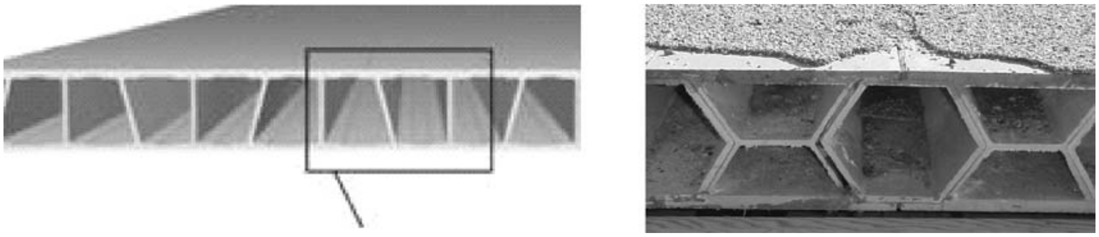


**Figure 3.3.3-1 Pultruded hollow core sandwich configuration.**

## 3.4 KEY MANUFACTURERS

Earlier discussion of manufacturing practices highlighted some of the advantages and disadvantages of each process to deck design and manufacturing. Reviewing the design approach taken by each deck manufacturer makes clear that they are all process driven, in that the distinct features of every deck derive from the processes used in its manufacture. Table 3.4-1 lists the names of current FRP composite deck manufacturers and the fabrication method used to produce their decks. The list is arranged by manufacturing method.

**Table 3.4-1 FRP Composite Deck Manufacturers**

| Name | Deck Type | Preferred Manufacturing Method | Address |
|---|---|---|---|
| Kansas Structural Composites | Type 1 | Hand Lay-up | 553 S. Front Street, Russell, KS 67665 |
| Infrastructure Composites, Inc. | Type 1 | Hand Lay-up | 7550 Trade Street,<br>San Diego, CA 92121 |
| Hardcore Composites | Type 2 | Vacuum Assisted Resin Transfer Molding | 618 Lambsons Lane, New Castle, DE 19720 |
| WebCore Technologies | Type 2 | Vacuum Assisted Resin Transfer Molding | 2000 Composite Drive,<br>Kettering, OH 45420 |
| Creative Pultrusions, Inc. | Type 3 | Pultrusion | 214 Industrial Lane, Alum Bank, PA 15521 |
| Martin Marietta Materials | Type 3 | Pultrusion | 2710 Wycliff Road,<br>Raleigh, NC 27607 |
| Bedford Reinforced Plastics | Type 3 | Pultrusion | 264 Reynoldsdale Rd.,<br>Bedford, PA 15522 |
| Fiber Reinforced Systems* | Type 3 | Pultrusion | 4636 Shuster Road,<br>Columbus, OH 43214 |
| Strongwell** | Type 3 | Pultrusion | 400 Commonwealth Ave.<br>Bristol, VA 24203 |

Note: * FRS offers a hybrid deck of an FRP pan and concrete deck.
** Strongwell does not have a FRP deck system, but offers FRP support beams.

## 3.5 DISCUSSION OF MANUFACTURING METHODS AND DECK TYPES

When fabricating components and structures from traditional construction materials, manufacturing is usually a matter of shaping, removing, and joining materials that are already solid. With FRP composites the situation is somewhat different than with metalworking (and, in some very specific ways, similar to casting) in that the material and the physical component are manufactured at the same time. Clearly, the synergy required in the early stages of designing the component, in this case bridge decks, must take into consideration how the component will be processed. This in turn influences the designer's mixing of constituents and composition of the laminate(s). The designs developed over the past decade distinctly reflect the manufacturing processes used to create them.

Since the 1950s, tremendous strides have been made in the processing of FRP composites; these strides have been motivated both by the need to reduce manufacturing costs and by the industry's desire to improve product quality and consistency. Also instrumental in this progress are more stringent environmental pollution limits, which are driving manufacturers away from open processes such as hand lay-up and toward more captive and automated systems.

This section discusses the basics of manufacturing processes typically used for manufacturing all structural FRP components, not just bridge decks. The purpose is to introduce readers to these methods and to show how differences in deck designs relate to the way they have been manufactured. The focus is on commercial processes rather than on such costly, high-precision methods as autoclave processing or high-pressure resin transfer molding, which are used in aerospace but not in deck manufacturing. Table 3.4-1 lists the process methods and their current applicability to bridge deck manufacturing. General descriptions of the processes are given in the following sections.

### 3.5.1 HAND LAY-UP OR OPEN MOLDING

The hand lay-up process is the most fundamental method of manufacturing still widely used in all industries. The basic procedure is shown in Figures 3.5.1-1 and 3.5.1-2. Fiber reinforcement is placed in position on the mold or plate and then saturated with resin. A crew then uses specialized rollers and paddles to work the resin into the fabric, fully wetting the layer. After determining that the layer is fully wetted, the crew repeats the process on succeeding layers until the lamination is complete. The component is then left to cure thoroughly, which takes from a few hours to overnight.

**3.5.1-1 Hand lay-up operation: dry filament placement.**

**3.5.1-2 Hand lay-up operation: fabric saturation.**

The advantage of hand lay-up is its low capital equipment costs and the low-to-moderate labor skill it requires. These factors usually make it the least expensive method for one-of-a-kind or limited production work. For complex parts, this may be the only feasible method. The disadvantage of this process is the variability in procedure and material properties due to the manual labor involved.

### 3.5.2 VACUUM-ASSISTED RESIN-TRANSFER MOLDING

The VARTM method employs a soft bag over the part to seal the mold so that a vacuum can be drawn under the bag. Once vacuum is achieved, the part is pressed onto the hard tool by atmospheric pressure. Resin ports on feed tubes are then opened to permit resin to flow into the mold and infiltrate the dry fabric reinforcement, as shown in Figure 3.5.2-1.

**Figure 3.5.2-1 Vacuum infusion process on Tycor reinforced bridge deck.**

The advantage of VARTM is the rapid infusion of large parts when the procedure works. As seen in Figure 3.5.2-1, infusion of large sections can be accomplished in minutes. Because the fiber reinforcement is compressed and locked in place by atmospheric pressure on the soft bag side, high fiber volume can be achieved. Good dimensional tolerance also is achieved because excess resin can just flow out of the vacuum ports.

However, because the resin flows indiscriminately under vacuum, the VARTM process requires volumetrically nearly solid sections in order to avoid forming resin-rich areas or resin pools in cavities. Also, any nonstructural materials such as foam core must be able to sustain the atmospheric pressure without crushing.

### 3.5.3 PULTRUSION

Pultrusion is a manufacturing process for producing continuous lengths of reinforced polymer structural shapes with constant cross sections. Raw materials usually consist of a liquid resin mixture and flexible textile reinforcing fibers. The process involves pulling these raw materials through a heated steel-forming die using a continuous pulling device. The reinforcement materials are in continuous form—for example, rolls of fiberglass mat or doffs of fiberglass roving. As the reinforcement is saturated with the resin mixture in the resin bath (called “wet-out”) and pulled through the die, heat from the die initiates the gelation (or hardening) of the resin. A rigid, cured profile is formed that corresponds to the shape of the die. Figure 3.5.3-1 shows the schematic of the pultrusion process.

The advantage of pultrusion is in the well-controlled and consistent dimensional profile of the structural components coming out of the die. Pultrusion is the most automated process now in use, requiring little hands-on labor. Internal die segments allow open or wrap-around shapes to be designed and details such as hollow tubes and trapezoids to be produced.

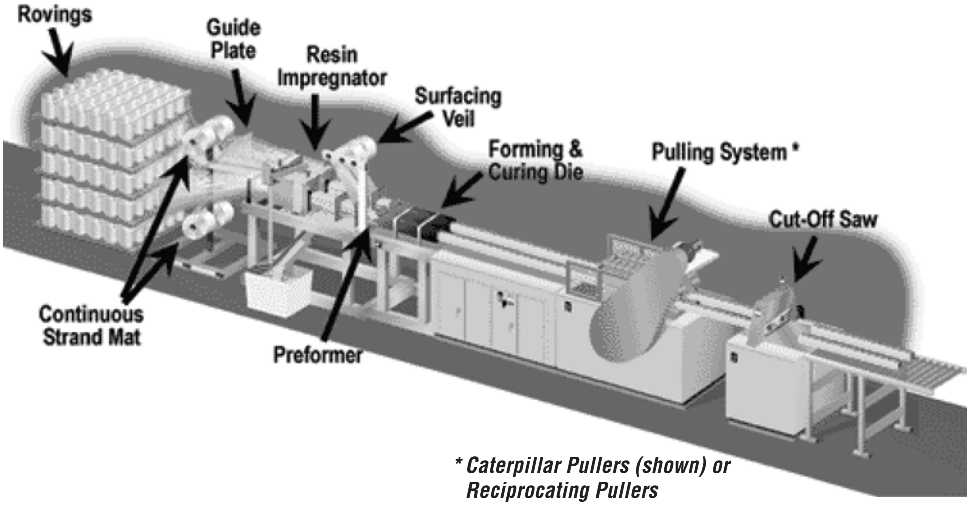


**Figure 3.5.3-1 Schematic of the pultrusion process.**

The disadvantage is that pultrusion produces long, narrow "barlike" profiles, so deck designs employing pultrusion must consider how to combine pultruded elements to create the necessary width.

### 3.5.4 FILAMENT WINDING

Filament winding is the process of fabricating FRP components by wrapping wet roving or fabric onto a single-axis rotating mandrel as shown in Figure 3.5.4-1. While no FRP bridge decks or components now in field service are being fabricated by the filament winding process, research and development of the process for fabricating deck components have been ongoing in the United States and Canada. For example, the University of Illinois completed NCHRP-IDEA Project 63, "Manufacture and Testing of a Filament Wound Composite Bridge Superstructure," demonstrating that filament wound bridge components could be fabricated at the 1/10th scale size.

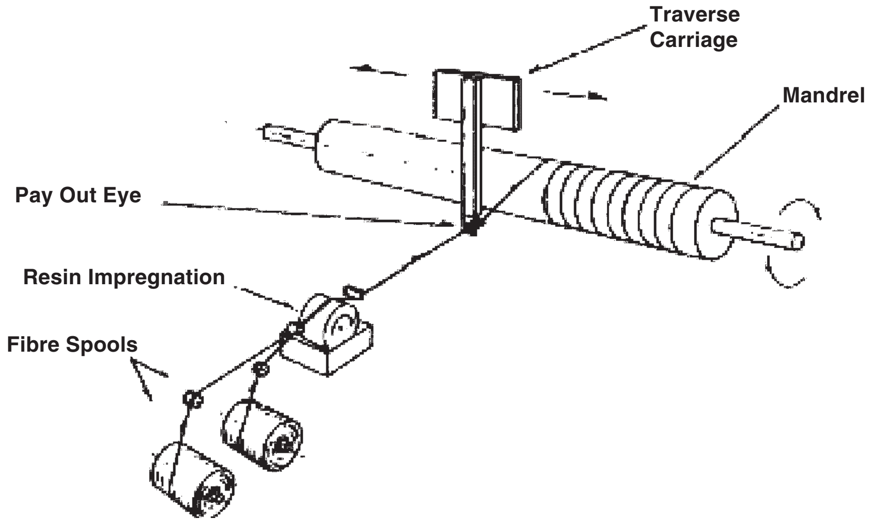


**Figure 3.5.4-1 General schematic for filament winding process (from www.tifac.org.in/news/acfil.htm).**

As in the pultrusion process, filament winding is an economical method for manufacturing tubular structures and structural columns. Once the setup is complete, the winding process can be autonomous almost from start to finish, with the preferred winding pattern and number of back-and-forth motions preprogrammed into a process controller. It is a wet-winding process, requiring a cure period afterwards to solidify the material.

### 3.5.5 ADHESIVE BONDING

Adhesive bonding is employed in all three types of deck designs, but is critical in Type 3 hollow core deck designs where the individual sections made by pultrusion are joined to form a full-width deck. In the manufacture of Type 1 decks, the facesheets and core webs may be fabricated separately and then press bonded together. Thus, the core-to-facesheet interface can be considered a bonded interface.

### 3.5.6 SECONDARY ASSEMBLY

Secondary assembly refers to any work or machining performed on the decks in order to prepare them for delivery and installation. This would include adhesively bonding components, drilling holes, and making repairs prior to shipment.

### 3.5.7 FINISHING

Application of gel coat or preparation of the top facesheet for wear surface installation in the field would constitute finishing.

## 3.6 GENERAL DELIVERY AND INSTALLATION PROCEDURE

Installation procedures for all deck types follow similar guidelines, which include

1. Delivery and acceptance inspection of the FRP decks,
2. Preparation of the bridge site according to specifications, and
3. Installation of the deck and other bridge components.

Installation specifications will dictate the connection method to be used for panel-to-panel connections and to anchor the decks to the superstructure. Specific installation procedures are based on designer, owner agency, or manufacturer's recommendations. Typically, the connection and anchoring methods selected are those that work best for a particular deck design.

## 3.7 TYPICAL DECK INSTALLATION

The following sections provide information on typical FRP deck installation practice and details of various FRP deck components. The FRP deck inspector and inspector trainee is provided this resource for general familiarization with manufacture and fabrication techniques. This manual is not intended to supplant FRP bridge deck installation manuals obtained for deck construction.

### 3.7.1 Panel Sizes

The FRP deck is typically manufactured in panels that are later attached together in the field. On bridges where the decks span in the transverse direction over longitudinal superstructure framing members such as stringers, the deck is composed of transverse panels 8 to 10 feet wide by about 30 feet long. These panels are typically 4 to 8 in. deep and serve as alternatives for conventional decks, meeting the existing roadway profiles and deck elevations. On bridges without superstructure elements supporting the deck, where the deck spans from abutment to abutment or from floor-beam to floor-beam, the deck sections are usually much thicker, with panel widths of 8 to 10 feet and lengths that suit the spanned distance.

Generally, FRP decks are made as wide as is practical to transport (i.e., 8 to 10 feet) and as long as will fit on a flatbed trailer. Because of the size limitations, almost all decks are joined in the field to create a seamless final installation.

### 3.7.2 INSTALLATION PROCESS

For typical FRP decks, all suppliers and contractors follow similar installation procedures. The following general sequence of events applies:

1. Deliver decks to bridge site,
2. Prepare decks for installation,
3. Prepare superstructure for deck installation,
4. Hoist and mount deck,
5. Secure deck to girders,
6. Prepare deck-to-deck interface,
7. Hoist and mount next deck section,
8. Join new deck section to previous deck section,
9. Secure deck to girders, and
10. Repeat 8 and 9 until complete.

The details of typical FRP deck installation are discussed in the following sections.

### 3.7.3 JOINT DETAILS

Details of the various types of joints in FRP deck construction are discussed in the following sections.

#### 3.7.3.1 Joints Between FRP Panels

In all existing installations, surface continuity is maintained by some active deck-to-deck connection that transmits shear across the interface. The deck-to-deck connections typically have one or more of the following features:

- Interference fit between edges either by shear keys or inserts,
- Tongue-and-groove connection with overlapping flanges, and/or
- Bonded connections.

### *3.7.3.1.1 Interference Fit with Shear Keys*

This method uses an insert or filler material in between decks to effect a shear lock between decks. This is similar to interlocking used between precast concrete slabs where grout is poured between the channel cavities of adjacent slabs to serve as shear keys. This has been used on several early decks, such as on the King Stormwater Channel Bridge. In this project, the connection is made with open C channels formed by adjacent decks as illustrated in Figure 3.7.3.1.1-1 Cement grout is cast into the channel to form a solid, interlocked shear key along the length of the mating faces.

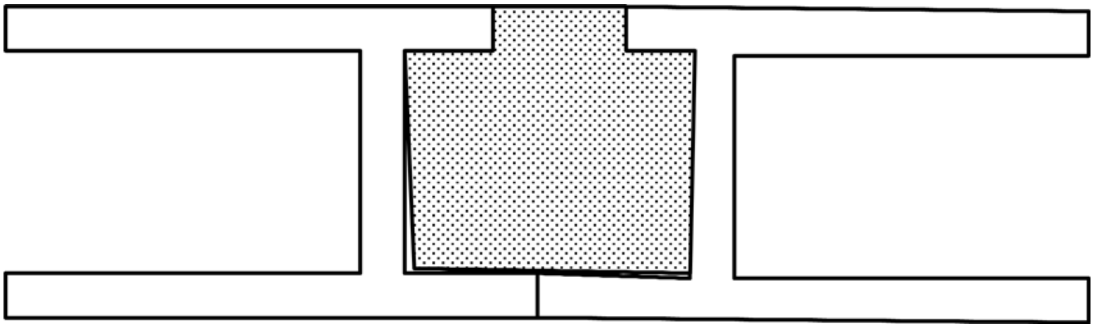


**Figure 3.7.3.1.1-1 Cast shear key connection.**

Another example is the shear key connection used on the Schuyler Heim deck shown in Figure 3.7.3.1.1-2. This is a secondary bonded shear key made with an FRP-wrapped wood core and bonded to the C-section of the adjacent deck edge. The exposed faces are lathered with epoxy adhesive and bonded into place during installation.

**Figure 3.7.3.1.1-2 Shear key on Schuyler Heim decks.**

Finally, a dry fitted shear key was used on the Jay Street Bridge to lock the decks into place. For this type of deck, the shear keys are bolted to the support girder at the crossover of the flanges, serving a dual purpose. This shear key detail is illustrated in Figure 3.7.3.1.1-3.

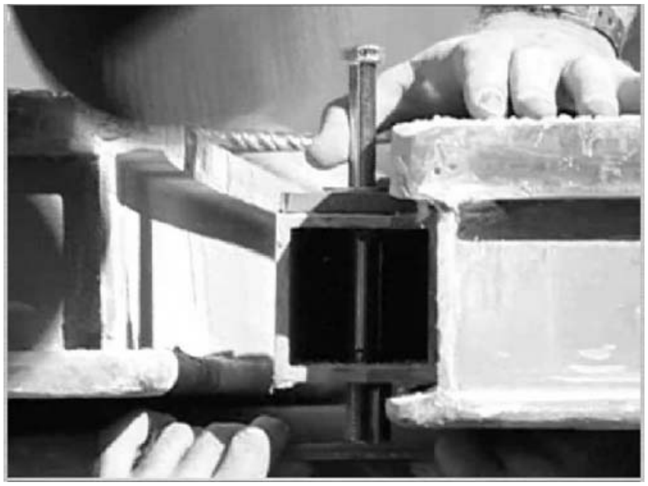


**Figure 3.7.3.1.1-3 Hollow tube shear key on Jay Street Bridge.**

Several approaches have been used to dress the connection and smooth the transition. In the King's Stormwater design, the shear key grout was filled flush to the surface and then overlaid with polymer concrete. For the Schuyler Heim decks, a strip of FRP reinforcement was applied across the seam-line of the connection. Polymer concrete overlay was then applied over the seam to eliminate it. On the Jane Stress Bridge, Kansas Structural Composites (KSC) filled the gap between decks with aggregate and then soaked it with resin to form a solid polymer concrete fill over the seam.

### *3.7.3.1.2 Tongue-and-Groove Connection*

This method uses a matched pair of edges similar to the set shown in Figures 3.7.3.1.2-1 and 3.7.3.1.2-2. The connection is an integral part of the deck units, so there is no separate shear key. Forces are transmitted between decks by direct contact. All the decks that have incorporated this field-joining method use adhesives to seal the connection. In these pultruded decks, urethane adhesive is used to bond the pultruded units to form a deck. For field bonding, epoxy or urethane adhesives have been used at the connections.

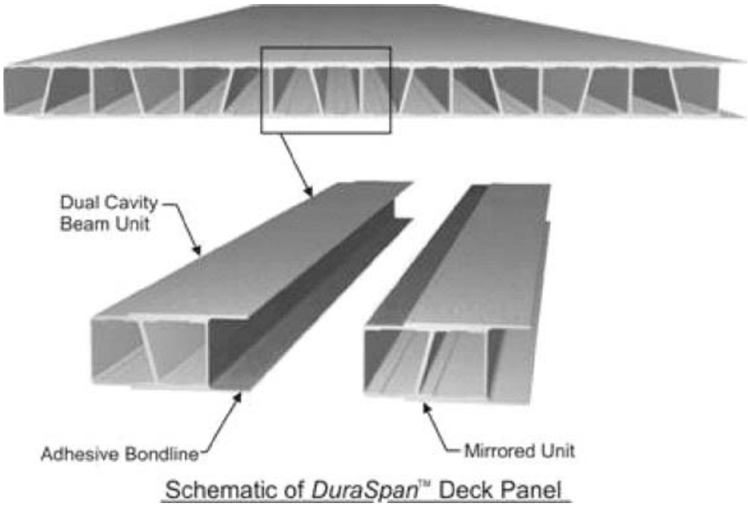


**Figure 3.7.3.1.2-1 Tongue-and-groove shear key deck connection on Schuyler Heim deck.**

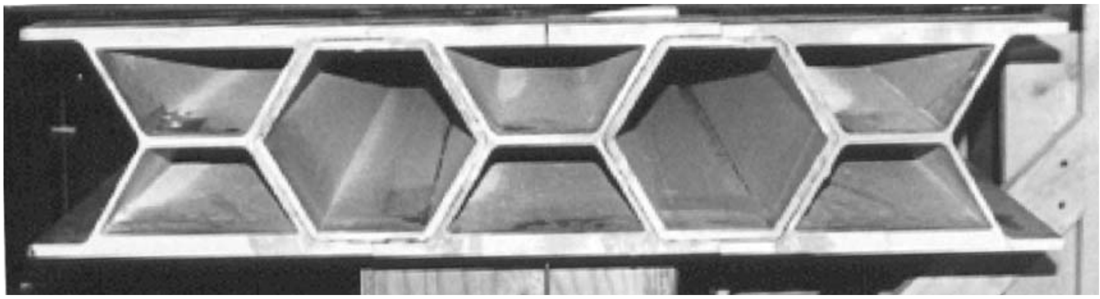


**Figure 3.7.3.1.2-2 Tongue-and-groove connection on pultruded deck.**

Another style of tongue-and-groove connection was used on the decks for the Salem Avenue Project in Dayton, Ohio (see Figure 3.7.3.1.2-3).

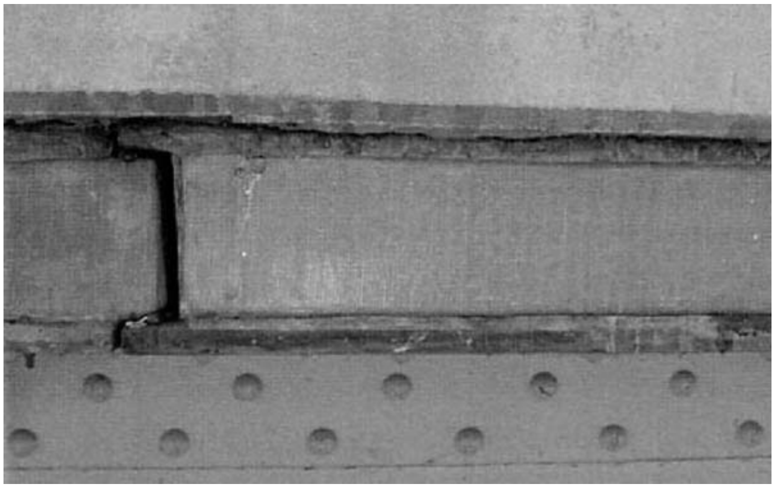


**Figure 3.7.3.1.2-3 Tongue-and-groove connection on Salem Avenue Bridge deck.**

In general, the installation procedure involves the following steps:

- Prepare the surfaces of the joining faces,
- Apply the adhesive to one of the faces,
- Press the decks together to squeeze the joint shut and smear the adhesive over the contact faces, and
- Let stand until cured.

### *3.7.3.1.3 Butt Joints with Shear Splice Plate Strips*

This method uses a butt joint between adjacent decks with splice plates field-bonded to the top and bottom of the decks to transfer load as shown in Figure 3.7.3.1.3-1. This technique was used on the Salem Avenue Bridge. In this installation, adhesive is applied to the edge of the decks to be connected (see Figure 3.7.3.1.3-2), and then the slice plate strips are bonded to the top and bottom of the decks (see Figure 3.7.3.1.3-3). Self-tapping screws were used to keep the splice strips in place while the adhesive cured. Currently, only one manufacturer has used this type of deck-to-deck connection.

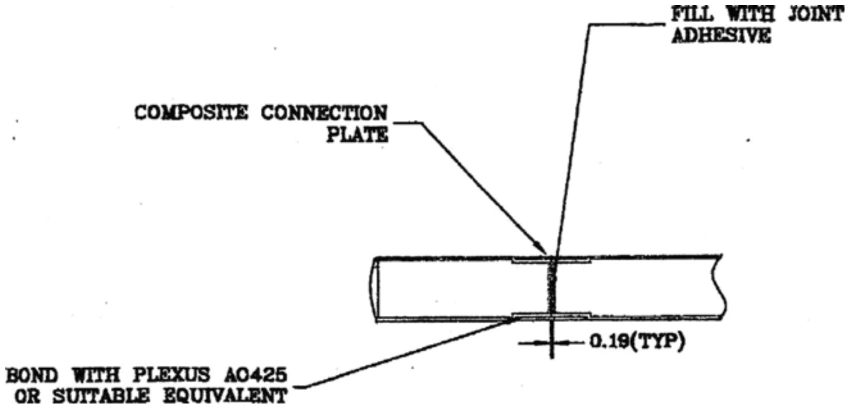


**Figure 3.7.3.1.3-1 Detail of deck-to-deck joint (Salem Avenue Bridge).**

**Figure 3.7.3.1.3-2 Application of adhesive on splice plates (Salem Avenue Bridge).**

**Figure 3.7.3.1.3-3 Mounting splice plates onto deck (Salem Avenue Bridge).**

### 3.7.3.2 Joints Between FRP Deck and Superstructure

The following sections discuss different details typically used to connect the decks to the superstructure.

#### *3.7.3.2.1 Shear Stud Connections*

This connection is adapted from the method used to anchor precast concrete slabs onto steel girders in which Nelson shear studs are welded onto the top of the steel girders through holes bored into the top and bottom facesheets of the composite deck (Figure 3.7.3.2.1-1). In the pultruded, hollow-cell core deck, for instance, the open center accommodates foam dams placed on the sides of the connection ports. One or more studs are used as required per connection pocket. After the studs are shot, the cavity is filled with grout to lock in the studs and deck. This setup is repeated down the length of the girder in a predetermined spacing based on design requirements.

To take up the irregularities between the girders and deck, a haunch is typically built up by flowing grout beneath the decks into the cavity between the top of the girder and bottom of the deck. The preparation of this is as shown in Figure 3.7.3.2.1-2.

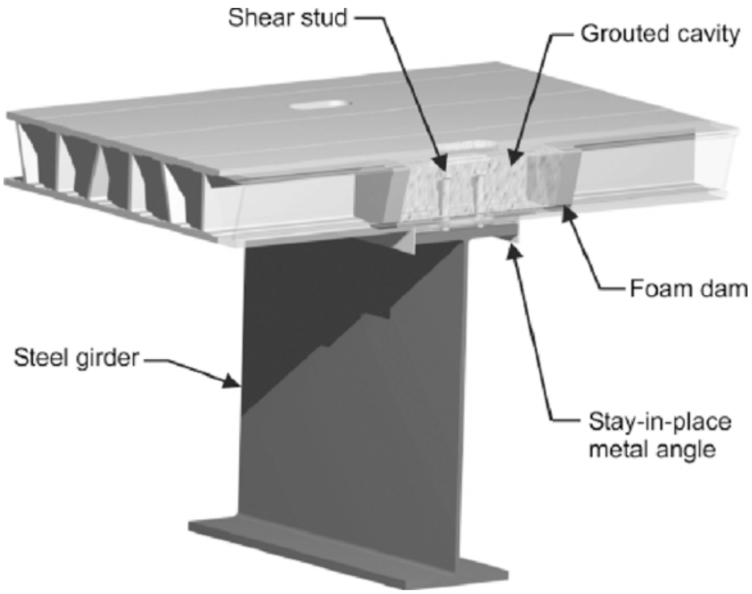


**Figure 3.7.3.2.1-1 Typical shear stud connections.**

**Figure 3.7.3.2.1-2 - Deck being laid down on steel girders; note the channel formed on the top flange for casting haunches.**

#### *3.7.3.2.2 Cast-in-Place Connections*

This connection is similar to the shear stud connection except that a different shearing member is used. In the King Stormwater bridge, a set of bent reinforcement bars cast into the underlying concrete-filled tubular girders act as the shear studs.

#### *3.7.3.2.3 Clip Connections*

This style of connection anchors the deck to the girders by vertically clamping it to the girder flange with steel side clips. Examples of these types of connections are shown in Figures 3.7.3.2.3-1 and 3.7.3.2.3-2 for the Jay Street Bridge.

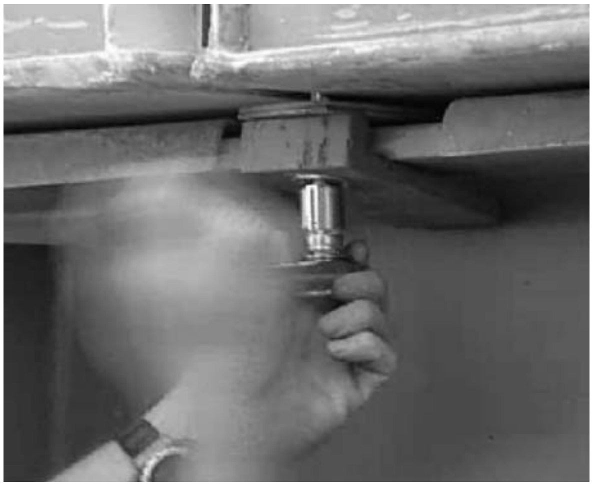


**Figure 3.7.3.2.3-1 Anchor clips used on Jay Street Bridge.**

**Figure 3.7.3.2.3-2 Girder clips for Jay Street Bridge.**

### *3.7.3.2.4 Bolted Connection*

This connection uses threaded Nelson studs to anchor composite decks onto steel girders. Like the shear stud, the threaded stud is welded to the girder through predrilled holes in the deck, as shown in Figures 3.7.3.2.4-1 and 3.7.3.2.4-2. This was used on the Schuyler Heim Bridge project. After the stud is secured, nuts and washers are torqued onto the bolts to lock down the deck. The nuts are secured with thread-lock, sealed, and the top facesheet holes are covered with a cap and wear surface.

**Figure 3.7.3.2.4-1 Carbon/fiberglass deck being installed in the Schuyler Heim lift bridge.**

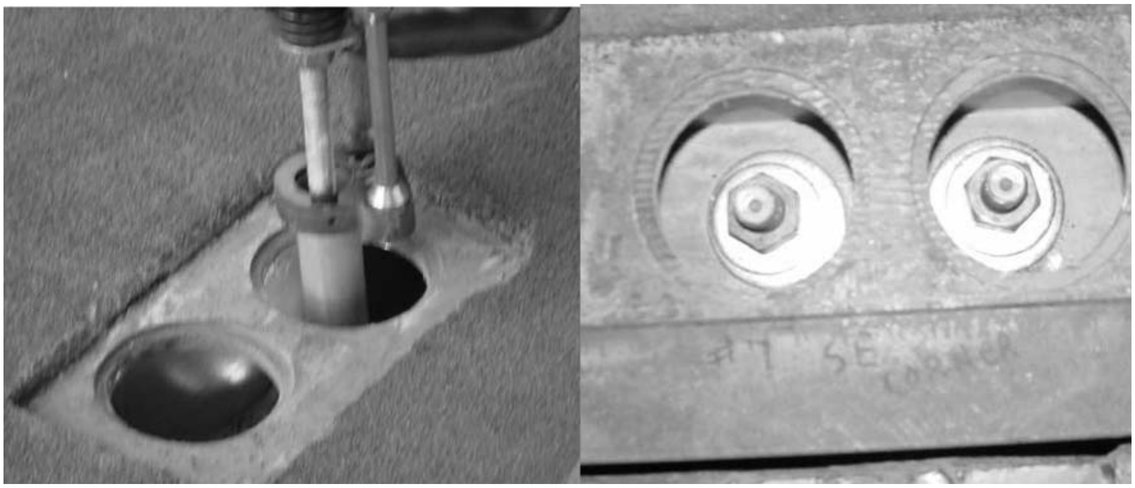


**Figure 3.7.3.2.4-2 - Decks are secured to girders through bolted connections.**

#### 3.7.3.3 Joints at Approaches

Approach joints for FRP decks range from open joints to soil backfill abutting the FRP decks. In some cases, conventional elastomeric materials have been used for the joints.

### 3.7.4 WEARING SURFACE

Various types of wearing surfaces have been used on FRP bridge decks. These surfaces range from conventional, field-applied bituminous overlays to factory-applied synthetic wearing surfaces.

### 3.7.5 CURBS, SIDEWALKS, PARAPETS, AND RAILINGS

Pedestrian walkways, parapets, railings, and curbs may be connected to a bridge in any of the following ways:

- Installed directly on top the FRP deck,
- Attached to an existing structure adjacent to the FRP deck, or
- Attached to an existing structure and connected to the FRP deck.

#### 3.7.5.1 Curbs and Railings Installed on Top of Deck

For this installation, the curb would be constructed on top of the bridge deck after deck installation. Curb may be prefabricated concrete or concrete-filled FRP delivered to site, or the curb may be constructed directly onto the deck, for instance, with cast-in-place concrete. The curb is typically anchored into the deck with studs or reinforcement bars. The reinforcing bars are embedded in concrete that fills the deck section underneath the curb. An example of the cast-in-place concrete curb on the Salem Avenue Bridge is illustrated in Figures 3.7.5.1-1 and 3.7.5.1-2.

**Figure 3.7.5.1-1 Finished cast-in-place curb, sidewalk, and parapet.**

**3.7.5.1-2 Reinforcing anchor details for the cast-in-place curb.**

### 3.7.5.2 Curbs and Railing on Independent Structure

On some bridges, curbs and railings are designed to be independent of the FRP decks. In these installations, the curbs and railings are connected to independent superstructure components or fascia girders. This type of construction helps to eliminate lateral loads being applied to the FRP decks, thereby making the FRP deck and the connection less susceptible to direct damage from vehicular or other type of lateral impact loads. Figure 3.7.5.2-1 illustrates this type of connection where the curbs, sidewalk, and railings are attached independently to stringers and separated by a gap from the FRP (as shown in the inset).

**Figure 3.7.5.2-1 Curb and sidewalk adjacent but not connected to the FRP deck.**

### 3.7.5.3 Curbs and Railings on Independent Structure but Connected to FRP Deck

On many FRP deck bridges, the railings are connected to independent fascia beams or girders but are also indirectly connected to the FRP decks. In these types of construction, the curbs are typically built on the FRP deck as discussed in an earlier section, while the railings abut the curbs but are connected directly to a fascia girder. Therefore, the girders resist all loads on the railings, while both the girders and the deck resist loads on the curbs. An example of this type of construction is illustrated in Figure 3.7.5.3-1.

**Figure 3.7.5.3-1 Figure showing railing connected to the curb and the fascia girder.**

# SECTION 4: SIGNIFICANT DECK DETAILS AND DAMAGE TYPES

## 4.1 OVERVIEW

This section presents FRP deck details and damage types and, in conjunction with Section 3, allows the inspector to understand the areas that need special emphasis during inspection. It also prepares the reader to understand the inspection techniques presented in Section 5.

Inspection of installed FRP decks covers two main areas: the external bridge components attached to or in the vicinity of an FRP deck and the deck element itself. More specifically, these two areas encompass

- External details—all the components and appurtenances on or near FRP decks that might be critical, directly or indirectly, for FRP bridge safety. This includes connections, joints, curbs, sidewalks, railings, and other such components of a bridge.
- Internal details—the FRP deck section itself, and includes the facesheets, cores, web components, and panel edges.

These details and intrinsic aging characteristics are described in detail in the following sections.

## 4.2 DECK EXTERNAL DETAILS

These details and locations should be inspected and evaluated during any inspection of FRP decks because they are likely to exhibit the first signs of distress that, if not identified and alleviated, could spread to larger areas. Figures 4.2.1-1 illustrating panel-to-panel connections and 4.2.2-1 illustrating deck-to-girder connections appear on pages 43 and 44.

### 4.2.1 PANEL-TO-PANEL CONNECTIONS

As discussed in Section 3, there exist several types of panel-to-panel connections. The panel-to-panel connection is probably the most accessible part of the bridge deck. It is also the most likely part of the deck system to develop problems because of improper installation, environmental swings, or excess loading. Experience with the Salem Avenue Bridge Project and ad hoc inspection/observation of bridge decks on the King Stormwater Channel, Tech 21, and Darke County bridges have shown that the first instance of problems generally occurs at the deck connections in the form of overlay/wear surface cracking or spalling.

#### 4.2.1.1 Interference Fit with Shear Keys

The main concern with the interference fit in this type of connection is the eventual "loosening" of the joint. The concern is that contact zones around the key will relax over time and cause the deck edges to shift vertically relative to one another. In that event, the likely symptom to identify would be stress cracking in the overlay or wear surface above the joint. Integrity of the wear surface is also a concern, but its condition will be readily detectible by visual inspection. Factors that might affect the integrity of the connection are

- Water intrusion combined with freeze-thaw cycling;
- Thermal expansion/shrinkage between dissimilar materials;
- Abrasion and wear between non-bonded surfaces in contact; and
- Cracking and deterioration of the key (in the case of grout or concrete).

For all these conditions, some of the main indications of problems would be

- Cracks in the overlay or wear surface;
- Noticeable deflection in one abutting deck element and not the other;
- Elevation differences between the edges of the decks;
- Chipping and pocketing of the shear key in the case of cast-in-place grout (where visible); and
- Water seepage on the underside of the deck.

#### 4.2.1.2 Tongue-and-Groove Connection

The same inspection issues apply here as in the keyed connection discussed earlier. These include

- Water intrusion combined with freeze-thaw cycling;
- Thermal expansion/shrinkage difference between male and female joints;
- Effects of large disbond and dry areas where there is no adhesive; and
- Local contact on the captive flanges leading to potential flange crippling or delaminations.

For all these conditions, some of the main indications of problems would be

- Cracks in the overlay or wear surface;
- Noticeable deflections in one abutting deck element and not the other;
- Elevation differences between the edges of the decks;
- Crippling of the flanges that may indicate joint movement;
- Large gaps at the seam-line, signaling joint movement; and
- Water seepage on the underside of the deck.

#### 4.2.1.3 Butt Joints with Shear Splice Plate Strips

Inspection concerns for butt joints are similar to those in other connections, with additional concerns stemming from the bonding sensitivity of the splice plate strips. Inspection issues for this connection are as follows:

- Water intrusion combined with freeze-thaw cycling;
- Thermal expansion/shrinkage differences between the decks and splice plates;
- Effects of large disbonds and dry areas where there is no adhesive; and
- Improperly mounted splice plates.

For all these conditions, some of the main indications of problems would be

- Cracks in the overlay or wear surface,
- Noticeable deflections in one deck element and not the other,
- Elevation differences between the edges of the decks,
- Pop-off of the splice plates and consequent wear surface damage,
- Large gaps at the seam-line that may signal joint movement, and
- Water seepage on the underside of the deck.

### 4.2.2 DECK-TO-GIRDER CONNECTIONS

The deck-to-girder connection is critical to the continued operation of the bridge. However, this connection by nature is well hidden and is the most difficult part of the deck anatomy to inspect directly. This discussion of deck-to-girder connections is limited to those connection details and inspection methods being used successfully on existing decks. The most common types of connections now in use are

- Shear stud connections,
- Clip connections, and
- Bolted connections.

### 4.2.2.1 Shear Stud Connections

This is one of the most difficult features of composite decks to inspect because the connection is hidden from plain sight from above and below. Thus, the integrity and durability of the connection can only be inferred by observing the deck's overall behavior and noting over time any performance changes in structural features surrounding the structural connection. Suggestions for observation include the following:

- Behavior, that is, movement of the deck under load. Is it deflecting or vibrating under traffic more than in the past?
- Noticeable gaps between the haunch or girder and bottom face of the deck are a strong telltale sign. Does a gap open and close between these contact surfaces under traffic?
- Observed rise and fall of the deck surface with temperature extremes may indicate a failed stud connection.
- Tap test around suspect connections on the top and from the bottom to detect signs of separation in the facesheet.
- Check for water seepage on the underside of deck through the connection holes.
- Any unusual localized vertical motions may indicate a weak or failed connection.

### 4.2.2.2 Clip Connections

The external feature of this anchoring method makes it more accessible to visual inspection than the blind shear studs when the underside of the decks is accessible:

- Observe any gaps between the haunch or girder and the bottom face of the deck to see whether there is noticeable vertical motion.
- A noticeable rise and fall of the deck surface with temperature extremes may indicate a failed bolt connection.
- If clips look intact but the deck surface still moves noticeably, tap test around suspect connections on the top to detect signs of separation in the facesheet.

- Again, any unusual localized vertical motions may indicate a weak or failed connection, so take steps necessary to diagnose the problem.

#### 4.2.2.3 Bolted Connections

The same inspection issues covering shear stud connections apply here as well. These include the following:

- Behavior, that is, movement of the deck under load. Is it bouncing more than in the past?
- Observe any gaps between the haunch or girder and bottom face of the deck to see whether there is noticeable vertical motion.
- A noticeable rise and fall of the deck surface with temperature extremes may indicate a failed stud connection.
- Tap test around suspect connections on the top and from the bottom to detect signs of separation in the facesheet.
- Check for water seepage on underside of deck through the connection holes. This may not indicate stud failure, but may require corrosion prevention measures.
- Any unusual localized vertical motions may indicate a weak or failed connection, so take steps necessary to diagnose the problem.

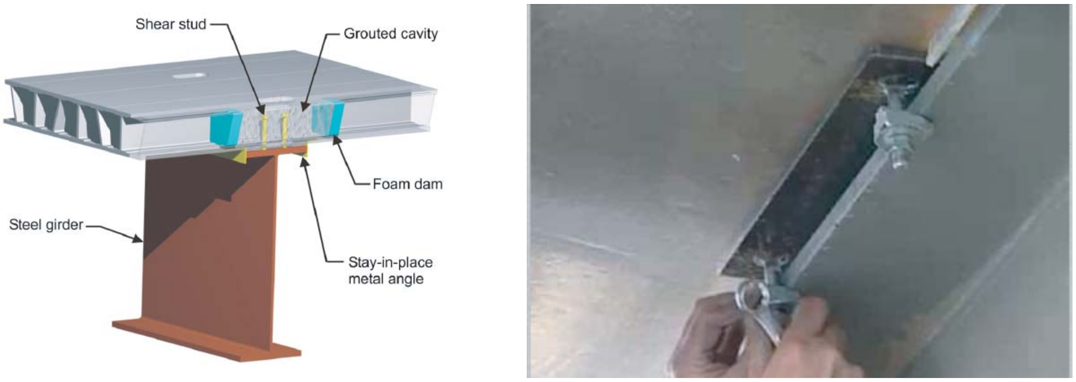
**Figure 4.2.1-1 Panel-to-panel connections.**

**(a) Interference fit with cast shear key**

**(b) T&G connection in pultruded hollow core**

**(c) Butt joint with shear splice plate strip**

**Figure 4.2.2-2 Deck-to-girder connections**



**(a) Shear stud connection**

**(b) Clip connection**

**(c) Bolted connection**

### 4.2.3 APPROACH JOINTS

Approach joints or deck components adjoining these areas on FRP decks are typically prone to damage due to differential movement between the approach and the deck. Both environmental and vehicular loading effects can cause this differential movement between the approach and deck. If such differential movement results in a permanent difference in elevation between the deck and the approach, then wheel transition over the joint will cause impact loads and damage at the approach joints. Signs of distress or damage at the approach joints include

- Spalling or delamination of wearing surface at the joints;
- Potholes, unevenness of wearing surface, or spalling at the joints;
- Difference in elevation between the approach and the deck; and
- Excessive bouncing or vibration of deck at the approaches as compared to the approach slab.

### 4.2.4 WEARING SURFACES

Important areas for inspection of wearing surfaces include areas around interfaces such as scuppers, curbs, and approach joints. Areas over panel-to-panel joints also are susceptible to damage or deterioration. The wearing surface is intrinsically susceptible to wear and tear as well as to vehicle-induced impact damage. It is also susceptible to construction quality and workmanship-related defects that could worsen while under use. Delamination, air pockets, peel off, potholes, and other such defects might therefore be found anywhere on the wearing surface.

During inspection, specifically look out for

- Delamination of the wearing surface;
- Unevenness, waviness, air pockets, and similar signs;
- Signs of abrasion, skid marks, potholes, and discoloration; and
- Separation and peeling off of wearing surface from the deck at joints, scuppers, and other interfaces.

### 4.2.5 CURBS, SIDEWALKS, PARAPETS, AND RAILINGS

Curbs, sidewalks, parapets, and railings are susceptible to horizontal loads that, depending on the connection details, can adversely affect FRP decks. Potential damage to the FRP deck may therefore be identified indirectly by noting distress or damage to the curbs, parapets, and railings. Some particular signs of distress and damage to look for include the following:

- Spalls, cracks, wheel marks, and other signs of impact on curbs;
- Signs of cracks and spalls at the curb-deck interface;
- Signs of distress and cracks where the curbs connect to the deck;
- Signs of vehicular or other impact on parapets and railings;
- Connections of railings or parapets to the deck;
- Damage, large deformations, dents, or bends in railings;
- Large spalls and cracks on parapets; and
- Cracks or other damage on the undersurface of the deck directly beneath the curbs, parapets, or railings.

## 4.3 DECK PANEL INTERNAL DETAILS

Most FRP decks are made with fiberglass reinforcement in polymer resin, and only in special cases are stiffer and more costly carbon fibers used. As discussed in Section 3, the stiffness of fiberglass structural laminates typically ranges from about 2.0 to 2.5 million psi, which is similar to concrete in compression. The advantage of FRP materials is their superior tensile stiffness and strength relative to concrete. It is this material characteristic that allows FRP decks to achieve high bending (flexure) rigidity with much less material. The motivation for using less material is lighter weight and lower material cost.

All composite decks except hybrid concrete decks (FRP plus reinforced concrete integrated into a deck) have some form of sandwich-type configuration—that is, a deep panel made of structural top and bottom surface sheets (typically called facesheets) integrally attached to a vertical-shear-resisting core. The core generally is lighter in weight per area and it may not carry in-plane forces, but must be designed to transfer shear loads between the facesheets.

Most details of the sandwich construction in a deck's panel are hidden from the inspector. Therefore, any potential problems must be inferred through symptoms seen in exposed areas or from unusual behavior or motions seen from above or below.

### 4.3.1 FACESHEETS

The facesheets comprise the loadbearing structural element of the bridge deck. Their construction depends on the method of manufacturing. Facesheets made by hand lay-up or vacuum infusion consist of multiple layers of FRP reinforcement in continuous fabric layers. Facesheets also can consist of sub-elements of a pultruded profile that must be bonded together to form the continuous facesheet. Whether the facesheets are continuous or bonded sections, their condition (particularly that of the top facesheet) is critical to the long-term performance of the FRP deck.

Be on the lookout for the following problems:

- Debonding, spalling, or fissure cracks in the wear surface that may signal deterioration of the facesheet surface and loss of adhesion with the wear surface.
- Abnormal undulations or mounds seen on the otherwise flat surface of the deck. This symptom could signal a delamination within the facesheet laminate or at the core interface that is causing the detached area to float noticeably.
- The presence of moisture stains on the underside, away from edges with no visible path for water collection. This could be a sign of porosity in the laminate.
- Blistering or noticeable bubbles on the surface or gelcoat where applied.
- Signs of vandalism, particularly indications of fire.

- Visible motion under traffic loads, which may indicate detachment of the wear surface or even the facesheet from the core.

### 4.3.2 SANDWICH CORES

The design of the deck core is generally what distinguishes the manufacturer and fabrication process of the FRP deck. The core is also the most hidden part of the deck and, consequently, the most difficult part to inspect without penetrating the facesheet. Thus, without resorting to instrumentation, the inspector must infer any problems from behavior at the top or bottom surfaces of the deck:

- Many of the symptoms discussed for facesheets apply here as well.
- For hollow core designs such as pultruded decks, water accumulation in the hollow cells is a potential problem.
- In deck cores manufactured by vacuum infusion or hand lay-up, foam is typically used in conjunction with fiber-reinforced members to make solid the space in the core where resin is not desired. The foam is nonstructural and contributes little to the stiffness of the deck, so its physical deterioration or detachment from the facesheet may not be critical unless moisture accumulates in the pockets and causes the facesheet to delaminate.

Pultrusions are typically narrow, repeating profile pieces bonded together to form the complete deck. The process allows internal features to be manufactured integrally with the outer section without the need to fill the core. Thus pultruded decks are generally one-dimensional profiles with webs to tie the top and bottom facesheets. Like solid cores, the web sections are generally hidden from direct inspection.

### 4.3.3 EDGES AND CLOSEOUTS

Edge and closeout panels are used to seal the ends of the deck and prevent unwanted access to the core. They may or may not be protected with gelcoat for weather and UV resistance. Closeouts are considered secondary structures and so are not as critical functionally should they become damaged.

## 4.4 VISUAL SIGNS OF DAMAGE AND DEFECTS IN FRP MATERIAL

Listed below are pictures and explanations of common types of damage that may be observed in FRP material.

### 4.4.1 BLISTERING

Blistering appears as surface bubbles on exposed laminate surfaces or gelcoated surfaces as shown in Figure 4.4.1-1. In the marine industry, blisters are generally attributed to osmosis of moisture into the laminate that exerts local hydrostatic pressure between layers, causing delamination and subsequent bubbling. This is normally a problem for marine craft because of the thinness of the shell. In FRP deck panels, osmosis to a degree that would cause blistering is rare. Trapped moisture subjected to freeze-thaw cycles could possibly cause this phenomenon, but it would most likely affect only the surface layer and not impact the deck's structural performance.

**Figure 4.4.1-1 Blistering on a gelcoated or laminated surface.**

### 4.4.2 VOIDS

Voids are submerged gaps within the laminates of a deck and are usually invisible if the composite laminate resin is pigmented or the surface is painted or gelcoated. If the void is large enough and grows progressively, it may appear as a crack on the surface. An example of this is shown in Figure 4.4.2-1 where the closeout of a foam-filled deck contained a large void that revealed itself as a surface crack along the closeout's edge.

**Figure 4.4.2-1 Internal voids in a closeout section of a foam-filled deck.**

More commonly, voids would be hidden and become the site where delamination begins over time. An example of a severe void is shown in Figure 4.4.2-2. The deck manufacturer's process and quality-assurance procedures are expected to prevent large voids that would degrade deck performance. Detection of such voids goes beyond visual inspection and can only be accomplished with signal penetration instruments.

**Figure 4.4.2-2 Manufacturing void found in the facesheet of a foam-filled deck.**

### 4.4.3 DISCOLORATION

Discoloration of the FRP laminate can be attributed to a number of sources, the most prevalent of which are as follows:

- Chemical reaction, surface deterioration due to prolonged UV light exposure, or exposure to intense heat or fire.
- Crazing and whitening from excessive strain, visible mainly on clear resins.
- Subsurface voids seen in clear resins because of poor wet-out or incomplete saturation. This is more a problem in manual hand lay-up processes.
- Moisture permeation of uncoated exposed resin, generally called “blushing.”
- Changes in pigmentation by manufacturer. This is not a structural problem.

### 4.4.4 WRINKLING

Fabric wrinkling is shown in Figure 4.4.4-1 and generally occurs because of excessive stretching or shearing of the fabric during wet-out. It is not a structural problem unless it interferes with the proper surface contact at the connection or impedes the bonding of the wear surface.

**Figure 4.4.4-1 Fabric wrinkling in laminated facesheet.**

### 4.4.5 FIBER EXPOSURE

In this damage scenario, the laminate exhibits fiber brooming or environmental exposure because of prior damage in handling as shown in Figure 4.4.5-1. Left unattended, the damage would make the fibers susceptible to moisture and contamination, leading to further laminate deterioration in the area.

**Figure 4.4.5-1 Exposed fiberglass fibers from installation damage.**

### 4.4.6 CRACKS

Damage due to impact can result in cracks on the facesheet emanating from the point of impact. Impact cracks are caused by impact from vehicles, debris, or stones, and they typically result in separation of material through the entire thickness of the laminate. Sometimes failure at a location with insufficient reinforcement fibers can cause damage that looks like impact cracks. Other types of failure, such as punching, can also initiate cracks emanating from the edges of the punched area. Examples of impact cracks are shown in Figures 4.4.6-1 and 4.4.6-2.

**Figure 4.4.6-1 Example of impact-induced crack of facesheet.**

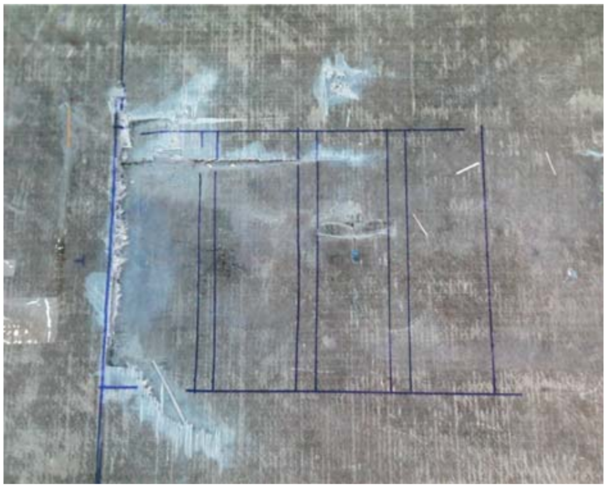


**Figure 4.4.6-2 Cracks and discoloration around punched facesheet.**

### 4.4.7 SCRATCHES

Facesheets can be abraded through improper handling in storage, during construction, with tools, and so forth, and this can result in scratches or shallow grooves on the FRP surfaces. These are usually just unsightly surface blemishes, but, if severe, they can develop into full-depth cracks under vehicular or environmental loads. Scratches are judged severe when the damage penetrates to the depth of the fiber and can lead to structural damage. An example of scratches is shown in Figure 4.4.7-1.

**Figure 4.4.7-1 Scratches on FRP surface.**

# SECTION 5: INSPECTION

## 5.1 TYPES OF INSPECTION

Various types of inspection techniques can be used to observe and note the condition of FRP decks. This section identifies eight available nondestructive evaluation (NDE) methods for inspection of FRP bridge decks. The section also identifies and discusses the equipment required for these inspections and outlines the general procedures for conducting the inspections. Six of the NDE methods outlined below require a higher level of experience or specialized equipment to conduct the inspection and to interpret the findings and would likely be obtained from NDE consultants under contract. The NDE methods are listed in order of increasing complexity.

It is anticipated that FRP bridge deck inspection will be performed using the two fundamental methods—namely, visual inspection and tap testing. More complex methods should be adopted only if the primary methods are not adequate to observe or assess unusual conditions or if the less complex method identifies an unusual condition that is not apparent based on descriptions available in this manual, necessitating more complex inspection.

### 5.1.1 VISUAL INSPECTION

Visual testing (VT) is the primary and most fundamental and widely used NDT inspection method adopted by bridge inspectors and is well suited for condition assessment of FRP decks. Visual inspection is the primary recommended method used to inspect the elements outlined in Section 5. The basic instruments for VT are a flashlight, a measuring tape, a straight edge, markers, binoculars, a magnifying glass, inspection mirrors, feeler gages, and a geologist's pick. Visual inspection is generally able to detect only surface defects; other NDE methods outlined below will be needed to detect subsurface defects.

Blistering or debonding below the wear surface may be detected using VT (see expansion joint figure in Figure 5.2.1.1-2, which reveals subsurface debonding). However, to help detect defects or cracking that might otherwise go unnoticed with visual testing, a static or dynamic live-load test can be done in conjunction with VT. A loaded dump truck or water truck can be used (Figure 5.1.1-1) to help reveal cracks and undesirable vertical deck movement.

**Figure 5.1.1-1 Dump truck placed on deck to reveal any cracks in FRP deck.**

### 5.1.2 TAP TESTING

Tap testing is the second most common type of NDE test performed on FRP bridge decks. Tap testing is fast, low in cost, and effective for inspecting composites for delaminations or debonding. Its mechanics are analogous to "chain drag" delamination surveys for assessment of reinforced concrete bridge decks. Based on the sound emitted by a coin or hammer tap, the test is capable of identifying the extent of a disbond or delamination. The larger the coin, the more remarkable the sound emitted as a result of a delamination or void.

Very little experience is required for this method. To tap test, the inspector taps the surface of the area of interest with the coin or hammer and then listens for a distinctive change in frequency when a void or delamination is encountered. A clear sharp ringing indicates a well-bonded structure, whereas a dull sound indicates a delamination or void. Note, however, that geometric changes within the structure also can produce a distinctive change in frequency that may be erroneously interpreted as a defect. Therefore, the inspector must be familiarized with the features of the structure. Tap testing does not require NDE certification, and thus a typical bridge engineer/inspector can perform this NDE method with very little training.

Depending on the location of the structure and the type and volume of traffic, traditional tap testing may not be feasible due to ambient noise. Relatively low cost and easy-to-use hand-held electronic units (Figure 5.1.2-1) are available that provide a quantitative, recordable indicator of a defect. Electronic units can be quite effective in a noisy environment. The coin tap test, however, is considered faster and more efficient for thick composites, varying thickness composites, and larger areas. The effectiveness of the tap test depends on the type of FRP deck and detail inspected. For instance, electronic tap testing works well for sandwich/core-type composite deck panels, but is not nearly as effective on pultruded deck sections such as the Duraspan deck due to their varying internal geometry. Instruments required for tap testing are a flashlight, a measuring tape, a straight edge, markers, and a large coin or small hammer.

**5.1.2-1 Electronic tap-tester unit.**

### 5.1.3 THERMAL TESTING

Thermography uses an ambient or artificial heat source to heat a sample and a heat-sensing device such as an infrared camera to measure the temperature variation within the object of interest (Figure 5.1.3-1). Heat can be applied to the surface by natural sunlight or by a pulsed light source, and then an infrared camera is used to measure the temperature variation of the subject. Subsurface variations such as discontinuities or voids in the material will cause slight changes in the wave infrared energy that radiates from the surface of the part. These discontinuities in the material or emissivity differences cause gradients in the isothermal contours that are detectable by the infrared camera. The advantage of active thermography is that it is completely noncontacting and uses remote heating and remote detection to make the measurements. However, thermography systems can be quite expensive, ranging in cost from about $10,000 for lower-end systems to $200,000 for sophisticated high-resolution image-processing systems.

The thermography process is quite simple: it consists of filming the object exposed to sunlight with an infrared video camera or using a combination pulsed flash/infrared camera unit (Figure 5.1.3-2). As with tap testing, the inspector must be familiar with the internal features of the structure so as to minimize data interpretation errors. Thermography does not require NDE certification, and a high level of experience is usually not required to interpret the data. Thus, a typical bridge engineer/inspector can perform this NDE method with some training. Thermography is effective for near-surface discontinuities such as delaminations, disbonds, impact damage, moisture, and voids.

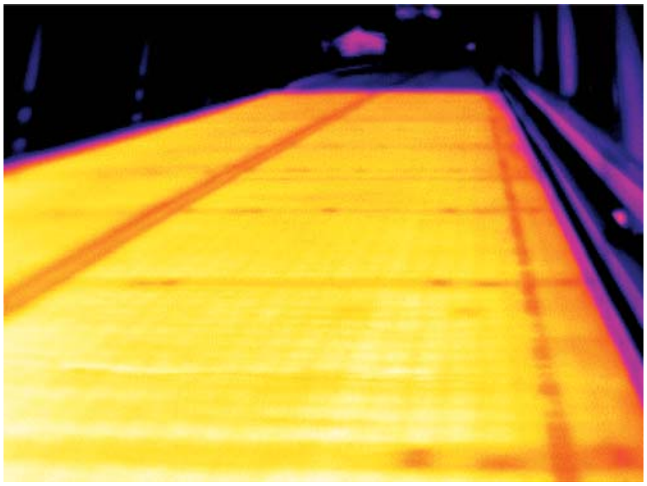


**Figure 5.1.3-1 Thermographic image of a bridge deck with ambient heat source. Deck splice locations and small delaminations are visible.**

**Figure 5.1.3-2 Thermal wave image processing unit and IR camera/heat source provide high resolution of local area.**

### 5.1.4 ACOUSTIC TESTING

In acoustic emission testing, an elastic wave is generated by the rapid release of energy from within a material. A structure under certain load levels produces acoustic sound, usually in the range between 20 KHz and 1 MHz. This sound generation is known as "acoustic emission" (AE). AE is simply the stress waves generated in the materials due to deformation, crack initiation and growth, crack opening and closure, fiber breakage, and delamination in composite materials. The elastic waves come through the solid to the surface where they can be recorded by one or more sensors/transducers. AE listens for emissions from active defects and is very sensitive to defect activity when a structure is loaded.

The required equipment includes AE piezoelectric sensors, couplant, multi-channel data acquisition hardware, and a fully integrated analysis and data acquisition software system (see Figure 5.1.4-1). The AE procedure consists of applying a couplant between the composite to be inspected and the sensors. Sensors are arrayed on the structure and connected to data acquisition equipment to detect, measure, and record the structure's acoustic emissions.

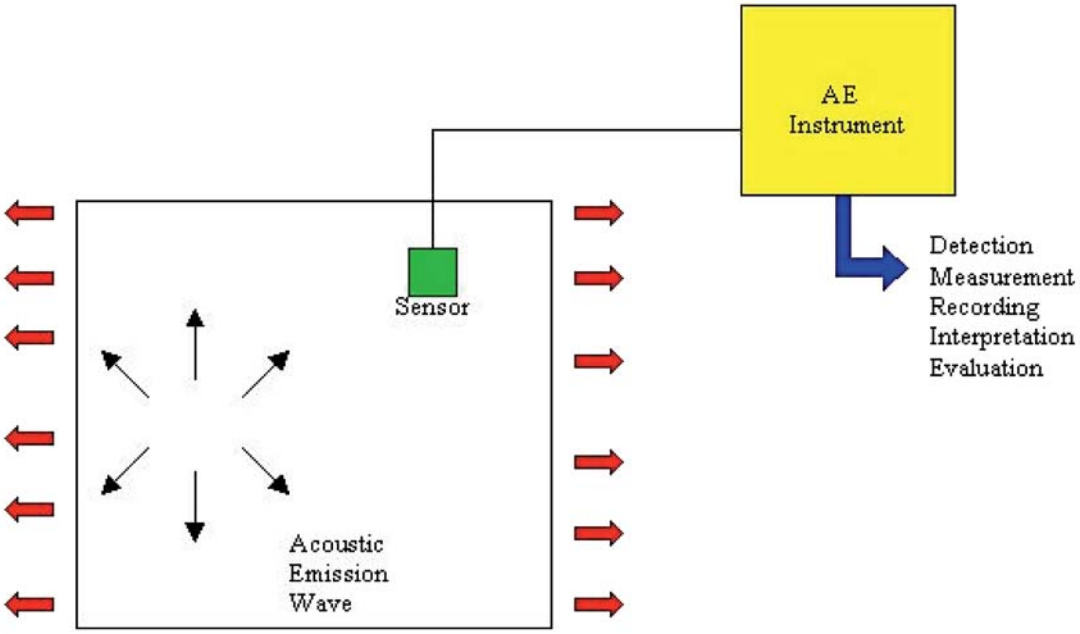


**Figure 5.1.4-1 Schematic of acoustic emission testing technique.**

AE is a global monitoring method that can be used to isolate the location of problem areas in the structure. The global AE cannot determine the configuration or size of the defect; however, it can be used to direct conventional NDE methods to the localized problem areas. AE requires a high level of skill and sophisticated equipment to conduct the test and interpret the data. The typical bridge maintenance engineer is unlikely to have the expertise to conduct the test and evaluate the results; therefore, it is expected that AE testing and the follow-up localized NDE testing will be contracted out. Typical discontinuities detectable by AE include delaminations, debonding, and fiber breakage. AE can also be used to determine a flaw's growth rate.

### 5.1.5 ULTRASONIC TESTING

Ultrasonic testing (UT) uses high-frequency sound in the range of 20 KHz to 25 MHz to evaluate internal volumetric condition of the material. This method involves applying a couplant to the area to be inspected and then scanning the area with a transducer (or probe) attached to a UT machine. The couplant serves as a uniform medium between the scanning surface and the transducer to ensure transmission of sound waves. Various couplants are used between the specimen and the probe. The transducer/probe contains a piezoelectric crystal that transmits high-frequency sound into the specimen and receives the returning or reflective signals for interpretation by displaying the signal in the form of an "A" scan or a "C" scan. The A scan display is similar to an oscilloscope display, giving the time of flight and reflection amplitude data. The C scan requires additional scanning equipment and displays a plan view of the detected defects. Typical discontinuities that are detectable include delaminations, disbonds, resin variations, broken fibers, impact damage, moisture, cracks, voids, and subsurface defects.

Unlike visual inspection, tap testing, or thermography, UT demands a high level of expertise to properly conduct the test and interpret the data. The inspector should be certified by the American Society of Nondestructive Testing (ASNT). UT should not be used to randomly scan the FRP bridge deck. Whenever possible, a first pass visual inspection, tap test, or AE testing should be conducted prior to UT testing to isolate the likely area of damage or defect. If visual inspection, tap testing, thermography, or AE detects discontinuities or damage, a localized UT can be performed to further characterize the location and size of the defect. Because the wear surface is rough and uneven and contains internal aggregate, using UT on the top deck surface is impractical unless a very good calibration can be achieved. The angularity of the aggregate will reflect sound waves, resulting in false indications. UT can easily be used on the bottom and sides of an FRP deck, however.

An alternative UT method known as "laser-based ultrasound" testing is a promising remote noncontact NDE inspection technique that combines the capabilities of optics and ultrasonics to detect, locate, and determine the size of flaws in a material. This technique uses a pulsed laser to generate ultrasonic waves that propagate inside the material and uses a second laser coupled to an optical interferometer to detect these waves. The advantage of laser-based UT is that it is a noncontact method that does not require couplant. No inexpensive portable laser-based UT units for large-scale field testing are readily available, however, so this NDE method is not currently practical for typical FRP bridge deck inspection.

The cost of a basic UT unit varies depending on the unit's sophistication (i.e., data retrieval, output format, etc.), and whether any automated scanning is included. A basic ultrasonic testing kit costs approximately $10,000.

### 5.1.6 RADIOGRAPHY

Radiography uses a penetrating radiation source such as X-rays or gamma rays and radiographic film to capture images of defects. Differential absorption of the penetrating radiation by the specimen will produce clearly discernible differences when recorded on radiographic film. Unlike ultrasonic testing, radiography cannot capture the volumetric characteristics of defects; however, it does provide a higher resolution of the planar aspects of defects. Defect resolution depends somewhat on the orientation of the defect with respect to the source and the film. Radiography requires access to both sides of the structure, with the radiation source placed on one side source and the film placed on the other side. Typical discontinuities that are detectable include some delaminations and some disbonds depending on the orientation, voids, resin variations, broken fibers, impact damage, and cracks. Radiography equipment can be hazardous if not handled or stored properly, and this method also requires a high level of skill both to conduct the test and to evaluate the radiographs. It is recommended that individuals conducting the test and evaluating the results be ASNT-certified.

An alternative to traditional radiography is the reverse-geometry digital X-ray. This is a low-level X-ray imaging system that eliminates the film sheet and uses television-type raster scanning combined with computer-read digital data from a detector unit. This method also requires access to both sides of the structure, with the source on one side and the detector/receiver on the other. With reverse geometry X-ray imaging, alignment of the X-ray source, object, and detector is not critical: three-dimensional images of the defect can be constructed. This method is much faster due to the scanning capabilities, it is much safer, and it requires no processing of radiographic film. This method also requires a high level of experience and expensive, highly specialized equipment.

### 5.1.7 MODAL ANALYSIS

The modal parameters method is a health monitoring NDE method that uses changes in the dynamic response of a structure to evaluate the structure's condition. The given structure is instrumented with an array of accelerometers, and prescribed dynamic load tests are performed to extract modal parameters with selected frequencies and mode shapes. Evaluating the structure requires modal parameters of the baseline structure (i.e., as originally built) and of the existing structure (i.e., in its current condition). In most cases, baseline parameters of a structure do not exist; however, the baseline modal parameters can be approximated from dynamic testing of the existing structure and from developing a numerical (finite element) model of the as-built condition.

This method requires capital investment for sensors and data acquisition equipment, staff training, and a relatively high skill level for the setup and data reduction and interpretation. Hence, the modal parameters method shall be used only if other techniques are unable to address concerns about hidden damages and overall structural performance of the FRP decks and its variation in time.

A stiffness sensitivity analysis is performed to evaluate stiffness changes in the structure by determining the damage location index. The damage index identifies local potential damage of structural members. Damage severity is then estimated for each predicted damage location. A current research project of the California DOT (Caltrans) and the University of California at San Diego is investigating a fracture mechanics–based approach to the modal parameters method to estimate the severity of the damage and to evaluate the impact of damage on the structure. This testing method requires a very high level of experience at the research or experimental level. However, the modal-parameters method is a viable option to evaluate whether the structure has undergone a change in stiffness.

Caltrans has successfully used the modal-parameters method for experimental health monitoring and NDE on a few bridges, two of which were strengthened by FRP composites and one of which is a hybrid design consisting of carbon-fiber reinforced plastic (CFRP) girders and a glass-fiber reinforced plastic (GFRP) bridge deck.

### 5.1.8 LOAD TESTING

In this nondestructive field performance evaluation test, a bridge is instrumented with sensors such as strain gages, accelerometers, and displacement sensors and then subjected to a known live load with a specific loading pattern. The instrumentation can serve the dual purposes of capturing the measured response of the structure during load tests and helping to monitor the long-term structural health of the bridge. Since a large proportion of the nation's FRP bridge decks were placed in service on a demonstration and technology transfer basis, a number of these new decks were instrumented and load tested with this method before the bridges were opened for service. Additionally, the load tests have been repeated at periodic intervals to assess any changes in deck response with time. This method is reserved for situations in which fundamental inspection techniques produce uncertain results.

This method requires an investment in sensors and data acquisition equipment and a relatively high skill level for the setup and data reduction and interpretation. Hence, load-testing method should be used only if other techniques are unable to address concerns about hidden damages and overall structural performance of the FRP decks and its variation in time.

Caltrans performed elaborate load testing on the Kings Stormwater Bridge after a routine field inspection that used the tap-test method identified possible separations between the CFRP-filament-wound girders and the concrete. Load tests indicated that the overall response of the bridge had not degraded and that the performance was about the same as when the bridge was first opened to traffic. Load testing was carried out with a wider scope and longer duration on the Schuyler Heim Bridge deck replacement project. The idea is that any damage at Category 1 or 2 affects the FRP deck panel stiffness locally and the superstructure more globally and therefore would influence the response of the bridge to dead and live loading.

The scope of load testing can vary depending on the purpose it's meant to serve and the resources available. For the purpose of inspection—that is, to verify bridge performance and detect potential damage for condition rating—limited-scope proof testing may be reasonable and manageable within the scope of a periodic inspection program. The following procedure is proposed:

- **Timing:** Perform load testing shortly after completion of bridge construction and at intervals that coincide with field inspection. Periodic testing should be performed under similar weather and environmental conditions.

- **Test load:** Use a truck heavy enough to generate considerable deflection in the deck. Truck weight of about the design load is recommended.

- **Test configuration:** Apply static loading by moving the truck along at least two symmetric lanes and stopping it at predefined locations along the bridge deck. Quarter points and mid-span are recommended, depending on the span length.

- **Test procedure:** Place the truck at specified locations and keep it stopped there for a specified time duration (e.g., ½ h). While the truck is stopped, inspect the bridge for signs of damage that could become apparent under load. At the end of stop time, collect deflection data and then move the truck to the next position. Repeat the procedure for all positions.

- **Instrumentation and data collection:** Measure deck span deflection at specified locations along and transverse to the bridge deck. It is recommended that deflection be measured at quarter points and mid-span along the bridge and at three points transversely at each location. Measurements can be taken using electronic displacement transducers, mechanical dial gages, or hand rulers and taut string, depending on the deflection amplitude, the recommended precision, accessibility, and span length. Measure deflection at the end of each stop time and again ½ h after the load is completely removed from the deck.

- **Criteria:** Bridge deflection under design or near-design load shall be less than the allowable deflection recommended by AASHTO. Deflection can also be compared with the designer's predicted deflection. Deflections shall be recovered almost entirely (e.g., within ± 5%) a specified time after unloading. Compare deflections at each period with those at initial and subsequent measurements, and report any difference. Significant differences indicate damage, and the change pattern—combined with results of visual inspection during load testing—may identify the approximate location.

Load testing can provide more complex data when performed by trained specialists using more sophisticated technology. Bridge owners and inspectors are referred to *NCHRP Research Results Digest 234: Manual for Bridge Rating through Load Testing* for more information.

### 5.1.9 COMPARISON OF METHODS

Potential inspection methods for FRP decks have been identified from aerospace technology, defense technology, shipbuilding, pressure vessels, and bridges. Detailed descriptions and discussions on the inspection methods are presented in the preceding sections. Methods such as visual inspection, tap testing, and ultrasonic testing are similar to those currently used in bridge inspection. More complicated methods such as acoustic, radiography, thermography, and so forth are seldom used in current bridge inspection programs. In Table 5.1.9-1, the various inspection methods are correlated to the types of defects they can help detect.

**Table 5.1.9-1 Inspection Method Applicability for Specific Defects and Deck Element Features***

| Technique / Features and Anomalies | Foreign Matter | Impact Damage | Cracks | Delaminations | Disbonds | Core or Internal Elements | External Elements |
|---|---|---|---|---|---|---|---|
| Visual | X | X | X | | | | X |
| Mechanical Impedance (Tap Test) | | X | | X | X | X | X |
| Thermal | | | X | X | X | | |
| Ultrasonic | | | | X | X | X | X |
| Acoustic Emission | | | X | X | X | | |
| Radiographic | X | | X | | | X | X |
| Laser Shearography and Other | | | X | X | X | X | |

*Table based on Report Reference 19, see p. 158 for reference.

Highway agencies can assume that techniques other than visual and tap testing might be warranted under certain circumstances. These can be provided by consultants and inspection firms. When used, inspection costs for services proffered by consultants will be different than those of a highway agency inspection unit's routine visual inspection or tap testing–based protocol. For reference purposes, the following cost data for field testing and inspection services were gathered and are provided, based on the research team's experience. These can be used to estimate comparative costs:

- Consultant Inspection Staff Hourly Fee (Technician/Inspector): $50 to $100 hourly depending on experience, including test equipment.
- Consultant Inspection Staff Hourly Fee (Engineer/Team Leader): $90 to $150 hourly depending on experience, including test equipment.
- It must be taken into account that radiography, X-ray, infrared, and load-test methods require specialized equipment and particular safety precautions.

> While the hourly rates above for inspection labor are representative for inspection staff skilled in these methods, additional daily fees ranging from a few hundred dollars to $1,000 or more may accrue for procuring equipment or support for these more complex, capital equipment–reliant inspection methods.

The visual method is by far the simplest and most important technique for inspecting FRP decks. Even in the aerospace and defense industries, inspectors rely on the visual technique for detecting in-service problems. It allows the inspector to rapidly detect gross imperfections or defects such as cracks, delamination, or impact damage. Visual inspection often can aid in detecting other imperfections such as porous adhesive fillets, lack of filleting, lack of adhesive, edge voids, discoloration, deformation, and other imperfections. To a trained inspector, the visual technique provides immediate clues while helping to identify areas that need more detailed examination. This technique requires operator interpretation, so inspectors should be trained to know what they are looking for and what any variation might mean to the strength and reliability of the component. The visual method has two drawbacks, however: (1) it does not lend itself well to quantifying the extent of damage and (2) it cannot be used to inspect components that are not directly visible.

Tap testing is another excellent and easy-to-use method for inspecting FRP decks. In the tap test, the inspector listens for any change in sounds emitted while tapping FRP surfaces. This method works best for inspecting sandwich panels with thin facesheets, but it can also be used on pultruded sections although there it is less effective in detecting delaminations or debonds. Still, most common problems on FRP decks can be identified using the tap-test method in conjunction with the visual technique.

Neither of these techniques requires any specialized equipment, and, with some training, both are easy to incorporate into a bridge owner's inspection program. Other techniques listed above are much more complex, expensive, and time-consuming to use. They require special expertise both to conduct the tests and interpret the results. Except for thermography, most of the more specialized methods are useful only for inspecting small areas. Therefore, these methods are best reserved for detailed assessment of potentially damaged or defective areas once they have been identified by either visual inspection or tap testing.

Of the various advanced methods, thermography and UT appear to be most practical for a bridge owner's inspection program. Already familiar with UT equipment and technique, bridge engineers and inspectors can more easily adapt this method for use on FRP decks. Thermography is relatively easy to use, requires no very expensive equipment, and provides output that can be visually analyzed, so it too could readily be adopted into an owner's inspection program. The other techniques, such as radiography and shearography (an interferometric system that uses an expanded beam of laser light reflected off the specimen) are more costly, involve expensive specialized equipment, and require considerable training to operate the equipment and interpret the results. Hence these other techniques, although useful and applicable, seem less likely to be adopted for regular bridge inspection programs. Bridge owners are more likely to contract out for these services when needed.

The modal-parameters method and load-testing method both investigate change in structural dynamic and static performance, respectively. When compared with previous results or baseline results, these techniques can identify changes in response and correlate as much as possible to the occurrence and accumulation of damage in the FRP deck. They can identify whether damage has occurred and sometimes determine the location and intensity of the damage. These techniques can be used on newly constructed decks as a means of health monitoring or to determine the extent of damage or its effects on the structural response parameters after signs of distress and damage have been observed. These techniques require an investment for sensors and data acquisition equipment, and a relatively high skill level for the setup and data reduction and interpretation. They offer a medium level of accuracy and reliability. Hence, modal parameters and load-testing methods should be used only if other techniques are unable to address concerns about hidden damages and overall structural performance of the FRP decks and its variation in time.

### 5.1.10 INSPECTOR QUALIFICATIONS, SITE SAFETY, AND OTHER ISSUES

The inspector and team leader qualifications should be as given in the *Code of Federal Regulations,* the latest edition of the *AASHTO Manual for Condition Evaluation of Bridges*, or as stipulated by the state DOT. Inspectors also should have additional qualifications and experience to identify the need for advanced inspection methods such as acoustic, ultrasonic, radiographic, and so forth and to interpret the resulting data. It is recognized that specialist nondestructive testing (NDT) engineers, employed by highway organizations or consultants, may be called upon to perform these inspections.

Traffic control, access, safety, equipment, and other site-related issues should be planned and managed by the inspection team leader in accordance with the U.S. Department of Labor's Occupational Safety and Health Organization, the *Manual of Uniform Traffic Control Devices*, and the *AASHTO Manual for Condition Evaluation of Bridges*. Any other standards or requirements stipulated by state or local regulatory authorities should also be followed when addressing issues related to the fieldwork.

## 5.2 INSPECTION OF FRP DECKS

Just as Section 4 divided the important details of FRP bridge decks into two main categories, the inspection of these details is discussed in the same two categories, namely

1. External details: All the components and appurtenances on or near FRP decks that might be critical directly or indirectly for FRP bridge safety. This category includes connections, joints, curbs, sidewalks, railings, and other such components of a bridge.

2. Internal details: The FRP deck section itself, including the facesheets, cores, web components, and panel edges.

The inspection of items in both categories is discussed in detail in the following sections.

### 5.2.1 INSPECTION OF EXTERNAL DETAILS

Guidance on inspection of details and locations on external components of FRP deck is provided in the following sections. These details and locations should be inspected and evaluated during any inspection of FRP decks because as they are likely the first to exhibit signs of distress.

#### 5.2.1.1 Panel-to-Panel Connections

The panel-to-panel connection should be thoroughly investigated during each inspection. As a minimum, the following should be checked during the inspection:

- Look for signs of reflective cracking and wear of field-applied joint splice material at the deck panel splice joints. Reflective cracking or oozing of joint material may indicate an improper fit or movement between adjoining panels at the joint (Figure 5.2.1.1-1).

- Look for signs of delamination or spalling of wearing surface in the vicinity of the joint (Figure 5.2.1.1-2).

- Check for signs of buckling, misalignment, and differential vertical or horizontal movement at the expansion joints by observing the joints at the top of the deck (Figures 5.2.1.1-3 and 5.2.1.1-4).

- Check for signs of opening or separation of joints (Figure 5.2.1.1-5).

- On decks where the joint is not covered by FRP laminates, use feeler gages on the underside of the deck to record the gap between the deck panels. An excessive gap should be monitored and flagged for maintenance action.

- Use feeler gages to check for any delamination of the adhered shear splice plates at butt joints.

- Use a small hammer to conduct tap tests in the vicinity of the joint. Any hollow sound should be further investigated using more advanced inspection methods to ascertain its extent and cause.

**Figure 5.2.1.1-1 Reflective cracking and oozed material at FRP deck-to-deck joints.**

**Figure 5.2.1.1-2 Debonding at joint and below wear surface.**

**Figure 5.2.1.1-3 Misalignment of deck-to-deck joint.**

**Figure 5.2.1.1-4 Misalignment of deck-to-deck joint.**

**Figure 5.2.1.1-5 Leakage through deck-to-deck joint.**

### 5.2.1.2 Deck-to-Girder Connections

The deck-to-girder connections are important parts of FRP deck bridges since the structural behavior of the deck is contingent on proper connection between the deck and the support structures. In addition, the connections are usually made using mechanical fasteners, which tend to work better with conventional material such as steel and concrete than with FRP. The fasteners or joints typically exert forces across the facesheet thickness, making the facesheets and the web components near the connections vulnerable to high stresses. The deck-to-girder connections therefore should be thoroughly investigated during each inspection, including the following specific steps:

- Observe the underside of the deck in the vicinity of support beams or abutments for discoloration, signs of flow, cracks, or any other signs of distress. The distress should be marked and monitored visually or with measuring instruments to determine whether it is active in response to traffic or other live-load application.

- On the underside of the deck, look for any separation between the deck and the haunch or other supporting superstructure component. Feeler gages should be used to measure the gap, and the gaps should be monitored. Gaps between the stringers and the deck could indicate warping or uplift of the deck. Further investigate any such signs to determine the cause of the uplift or warping. See Figure 5.2.1.2-1.

- Observe and note any cracking of haunch grout material.

- Examine neoprene pads or concrete haunches at deck supports to ensure the FRP deck is bearing fully on the stringer. Shim any gaps after fully evaluating the cause of the uplift or gap.

- On the underside of the deck, perform tap tests on the deck in the vicinity of the supports. Mark any hollow-sounding areas for monitoring. If the hollow areas are extensive, investigate them further using advanced inspection techniques such as thermal imaging or acoustic or ultrasonic testing.

- Check clip-type connections for soundness and tightness. Check the bolts on the clips to ensure that they are tight. Tap the clips with a small hammer to ensure their snugness. See Figure 5.2.1.2-2.

- If connectors such as Nelson studs or clip bolts are not accessible for visual examination, static or dynamic live-load testing could assist in determining the proper operation of these connectors.

- Visually examine the FRP deck and the steel stringers for scratches, abrasion or other signs of movement at the clip connections. Check for any cracks in the FRP deck area bearing against the bolt for the clip connection.

- On the top of the deck, watch for any cracks in the wearing surface, or deformation or unevenness of the deck at the stringer or approach supports. This may be a sign of differential movement between the deck and the supports. See Figure 5.2.1.2-3.

Figure 5.2.1.2-1  FRP deck and connection studs.

Figure 5.2.1.2-2  Clip type connection.

Figure 5.2.1.2-3  Crack in haunch.

### 5.2.1.3 Approach Joints

As discussed in Sections 3 and 4, approach joints on most FRP deck bridges consist of soil fill abutting against the side of the deck; formed or other elaborate joints typically are not used. Despite the rudimentary nature of approach joints on FRP deck bridges, the following steps should be performed as a minimum, when inspecting them:

- Observe the approach joint area for differential movement between the deck and approach. Investigate any difference to ensure it is not due to damage or crushing of the FRP deck.

- Inspect the underside of the deck for the presence of gaps or voids. If neoprene or other bearing material is used, inspect it to ensure that the deck section is bearing fully on the abutment. Use feeler gages and a flashlight to inspect for gaps. Gaps should be marked and monitored under vehicular loads. Gaps affected by vehicular loads should be shimmed at the earliest. See Figure 5.2.1.3-1.

- Check the end of the deck for distress due to soil pressure or other approach loads. If possible, try to observe the condition from the underside of the deck. Inspection mirrors or similar instruments can be used to observe the condition of the deck where it is not directly visible.

- If there is a formed joint, check to ensure that it is functioning properly. Inspect expansion joints to ensure that there is enough room for expansion. If the joint is frozen due to debris or other material, note and flag it for maintenance action.

**Figure 5.2.1.3-1 Shimming of gap between deck and abutment.**

### 5.2.1.4 Wearing Surfaces

The wearing surface is generally the most abused portion of any deck. On an FRP deck, the wearing surface also helps provide better ride quality and protects the top facesheet of the deck. The wearing surface inspection, at a minimum, should include the following activities:

- Chain drag is an effective way to locate distressed areas of the wearing surface. To an experienced inspector, the difference in the sound of chain drag could signal delamination location, extent, and whether the delamination is between the wearing surface and the top facesheet or between the facesheets and webs. Once delamination is identified, more detailed investigation via tap testing or thermography could help determine the nature of the delamination.

- Check for signs of blistering/debonding of the wearing surface. Although it can be difficult, try to determine whether the debonding or delamination is between facesheet and wearing surface or within the facesheet itself. Use a well-calibrated tap tester or the UT method to help identify the location of delamination. Figures 5.2.1.4-1 and 5.2.1.4-2 show an example of delamination and failure of the wear surface.

- Check for buckling of the wear surface. Visual signs as well as the tap test can help identify buckling. See Figure 5.2.1.4-3.

- Carefully observe areas over joints and around other openings in the deck such as scuppers. These areas are susceptible to cracking due either to differential movement between adjoining sections or to stress concentration at corners of openings.

**Figure 5.2.1.4-1  Delamination/failure of wear surface on an FRP deck.**

**5.2.1.4-2 Wear surface debonding.**

**Figure 5.2.1.4-3 Buckling of wear surface on FRP deck.**

### 5.2.1.5 Curbs, Sidewalks, Parapets, and Railings

Curbs, sidewalks, parapets, and railings are susceptible to horizontal loads and impacts. Typical curbs, parapets, and railings are shown on Figures 5.2.1.5-1 and 5.2.1.5-2. An inspection of curbs, sidewalks, parapets, and railings should include the following activities at a minimum:

- Visually inspect curbs for spalls, cracks, wheel marks, and other signs of impact. If such signs are evident, conduct hammer sounding on the curbs and tap test on the FRP in the vicinity of the impact location on the curb. Also check the connection of the curb to the deck or other part of the superstructure for cracks, delaminations, spalls, or other signs of distress. See Figures 5.2.1.5-3 and 5.2.1.5-4.

- Visually check interface between curbs and deck for separation or gaps, as well as for signs of cracks and spalls at the curb-deck interface. See Figure 5.2.1.5-4.

- If distress is identified on any FRP components, then investigate the distress areas further with advanced inspection techniques. Conducting further inspection is important, as the visible damage may be only a small portion of actual damage within the FRP deck. For example, in Figure 5.2.1.5-5, the deck exterior does not show major signs of distress, but the dissected section shows cracks in the core. Although such cracks in the core may not be identifiable without dissection, ultrasonic or acoustic methods may provide some idea of the likelihood of damage.

- Visually inspect parapets and railings for signs of vehicular or other lateral impact. Observe the base of the railing and parapet at the junction with the FRP deck for any signs of cracks, yielding, spalling, or other signs of distress. If distress is identified, then investigate the FRP area in the vicinity of the impact location for signs of damage. As in the case of curbs, use advanced inspection techniques if the FRP deck appears distressed or damaged as a consequence of the impact on the railing or parapet.

- Inspect the connections of railings to the deck or other parts of the superstructure. Use a small hammer to determine whether the connections are tight, and bolts are snug. Note any connections that may be broken, loose, deteriorated, or damaged.

- Note any large spalls or cracks on concrete curbs and railings. Also check for damage, large deformation, dents, or bends in steel railings.

- Check for cracks or other damage and distress on the underside of the deck directly beneath the curbs, parapets, or railings. Use a tap test to check the area if the damage appears to be on an FRP deck component.

**Figure 5.2.1.5-1 Typical steel railing connected to FRP deck.**

**Figure 5.2.1.5-2 Typical concrete parapet.**

**Figure 5.2.1.5-3 Underside of railing showing connection of railing to deck.**

**Figure 5.2.1.5-4 Concrete cracking at the parapet-to-FRP-deck interface.**

**Figure 5.2.1.5-5 Cracks in the web of FRP deck.**

### 5.2.2 INSPECTION OF INTERNAL DETAILS

As discussed in Section 4.3, FRP decks are largely sandwich panels composed of the following sub-elements:

- Top facesheet external laminate,
- Center core section and its components,
- Bottom facesheet external laminate,
- Panel-to-panel connections,
- Secondary components such as closeouts, and
- Penetrations and holes.

Visual access to all of these sub-elements is generally restricted because of the box construction of decks. Assessment of the proper functional behavior of these deck components must, therefore, be made indirectly through observation and inspection of the observable surfaces. This reduces the domain of the inspection to the following FRP deck features:

- Surface of the top facesheet,
- Edges of the decks,
- Deck-to-deck connection, and
- Surface of the bottom facesheet.

What is important are the appearance and performance of the deck system in service. Aside from the wear surface, visual indicators of problems or potential problems may not appear immediately after installation, but arise over time. Even FRP decks with considerable internal damage can remain quite robust overall, with problems occurring only in the vicinity of the damage. The following are the symptoms most likely to be encountered on an FRP deck system and probable causes that might drive the decision to pursue the inspection further.

### 5.2.2.1 Facesheets

External laminates or facesheets are the deck elements most likely to be directly affected by vehicular and other loads. The top facesheet is the most vulnerable component because it directly bears all vehicular loads and also is under compressive stress. Inspect facesheets thoroughly through visual and tap testing. The wearing surface makes it difficult to inspect the top surface of facesheets, but make every attempt to inspect the facesheet indirectly as discussed below:

- The condition of the wear surface is also an important aspect of inspection because many deck performance problems are reflected on the wear surface. Even when wear surface adhesion to the deck surface is good, stress cracking may still occur from excessive movement or strain within the facesheet. Decks made with bonded pultruded sections can exhibit line cracks at the factory bondline, signaling excessive motion of the adhesive joints as shown in Figure 5.2.2.1-1.

- Look for local bubbles in the facesheet. Decks are typically flat panels, and any unusual bubbling, rise, or undulation should be investigated further. Use the tap test to determine the extent of the bubble. On top surface, determining whether the bubble is in the wear surface or in the deck laminate will generally be difficult. Advanced inspection techniques such as thermography, UT, or a well-calibrated tap test can help determine whether the bubble is in the facesheet. An example of this anomaly is shown in Figure 5.2.2.1-2.

- Look for signs of surface deterioration from wear and tear and environmental exposure. Such damage would generally be as apparent from wear marks, fiber exposure, discoloration, stretch marks, and so forth.

- Look for impact damage on the facesheet. An extreme example is shown in Figure 5.2.2.1-3 where punch-through has resulted from impact.

- Look for damage from acts of vandalism such as that shown in Figure 5.2.2.1-4 where vandals attempted to burn the FRP material.

- Persistent moisture residue around an area could indicate the presence of voids, delamination, or holes as shown in Figure 5.2.2.1-5.

- Delamination is typically classified as a separation of plies within the facesheet laminate, but such separation can also occur at the boundary layer between facesheet and core and may appear similar to delamination. Buckling occurs when the facesheet snaps through, but can recover flatness. Although this type of defect would be difficult to see, Figures 5.2.2.1-6 through 5.2.2.1-8 illustrate such defects in a laboratory setting.

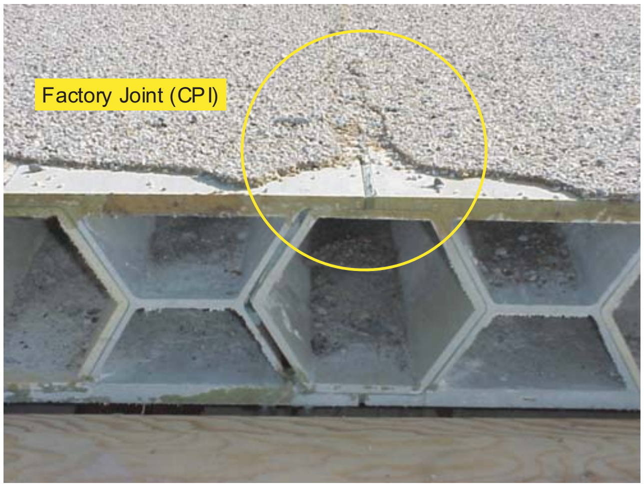


**Figure 5.2.2.1-1 Factory joint on pultruded sandwich deck (Salem Ave. Bridge).**

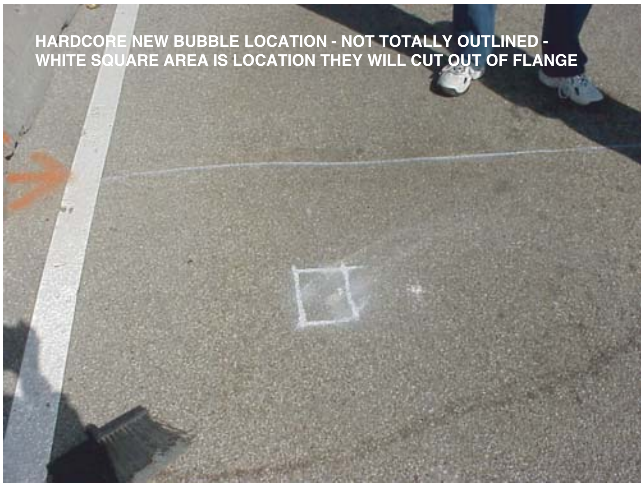


**Figure 5.2.2.1-2 Section of deck with a 3-ft-diameter bubble.**

Figure 5.2.2.1-3 Punch-through of the deck from impact (Schuyler Heim Bridge).

Figure 5.2.2.1-4 Attempted ignition of deck material by vandals.

Figure 5.2.2.1-5 Water found within core of deck after drilling.

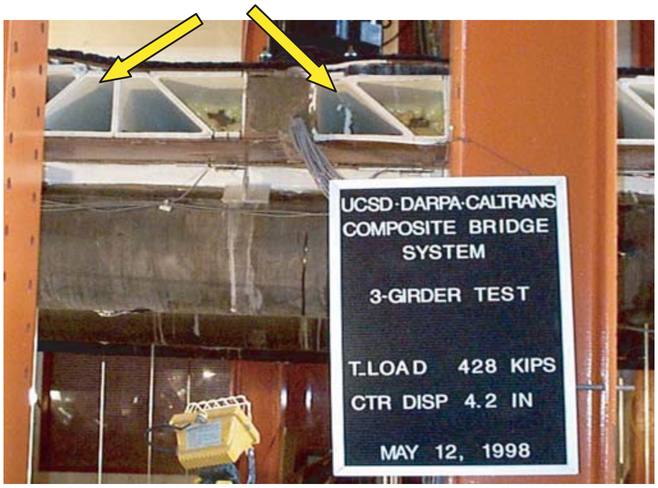


**Figure 5.2.2.1-6 Facesheet delaminations and buckling at maximum load.**

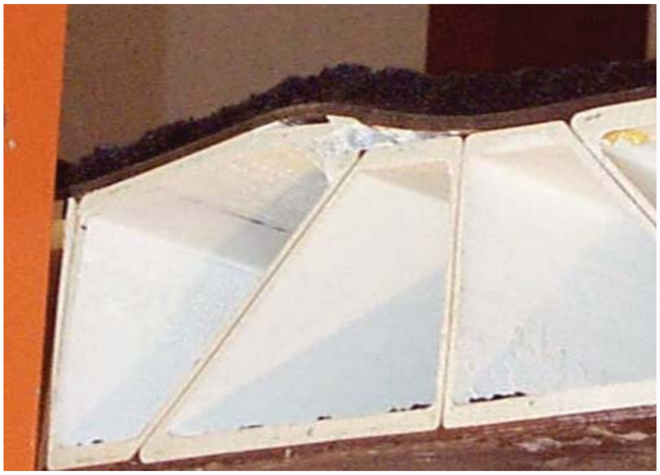


**Figure 5.2.2.1-7 Tearing of core leading to facesheet buckling.**

**Figure 5.2.2.1-8 Example of thin facesheet crippling on foam sandwich deck.**

### 5.2.2.2 Sandwich Cores

Visual inspection of sandwich cores and web components is unlikely since they are typically sealed within the facesheets. Inspecting these components therefore entails the use of advanced techniques such as radiography or indirect methods such as impulse response and load testing. Furthermore, as discussed in the previous section, any failure of the core or web would show signs of distress in the facesheets and wearing surfaces before the defect would seriously threaten deck safety. Hence, the most practical way to inspect sandwich cores is to indirectly infer the health of the core from inspection of facesheets and other visible deck components. To indicate how distress and possible failure of a sandwich core component might look, examples of laboratory testing of FRP decks are illustrated in Figures 5.2.2.2-1 and 5.2.2.2-2.

**Figure 5.2.2.2-1 Foam sandwich deck failure under line load.**

**Figure 5.2.2.2-2 Example of web failure and debonding of thick facesheet from core.**

### 5.2.2.3 Edges and Closeouts

Edges and closeouts transfer shear across panel-to-panel joints or carry the reactions at the supports. In addition, and depending on the connection or support details, these regions also see rotational and torsional loads. The edge and closeout sections are therefore susceptible to distress. Inspect this area in the manner previously described for inspecting panel-to-panel connections and approach joints.

## 5.3 FREQUENCY AND DEPTH OF INSPECTION

FHWA requires that all bridges be inspected at least every 2 years. However, it is recommended that FRP bridge decks be inspected annually at a minimum. The need for more frequent inspections is due to several factors, among them the newness of FRP material; its limited track record; limited knowledge about long-term environmental effects on FRP material and its durability; the proprietary nature of deck section designs; limited knowledge of connection behavior, the magnitude of stress and strains, and so forth. Taking all these factors into consideration, the state bridge engineer should establish the specific inspection frequency for each bridge. Some factors that may influence inspection frequency are age, damage, stress range, detailed features, and traffic volume. The factors used to determine the inspection frequency should be recorded in the bridge report for future inspections. The bridge inspector should be familiar with the internal geometry and the fabrication method of the FRP deck, and this information also should be on record in the bridge report. For newly installed FRP bridge decks, individual deck panels should be inspected thoroughly prior to installation, and a load test should be performed on the newly installed bridge deck before opening the bridge to traffic. The data gathered from the initial inspection and load test should be used as a baseline evaluation for future inspections and load tests.

# SECTION 6: RECORDKEEPING

This section elaborates on a uniform method of annotating and describing damage and findings of FRP deck inspection.

## 6.1 NEED FOR STANDARD NOMENCLATURE FOR PARTS, LOCATIONS, AND DAMAGES

In order to have uniformity in recording and evaluating field conditions, both across various structures and over time on the same structure, there is a need for standard nomenclature to describe the location, parts, and condition of the FRP components. Some standard terms and descriptions of FRP components are discussed in earlier sections. In addition to these, each inspection agency should compile its own list of standard nomenclature and definitions relating to FRP decks.

## 6.2 PROCEDURE FOR RECORDING OBSERVATIONS

Observations from FRP deck inspection must be recorded to clearly indicate the location, extent, type, and severity of any damage. Clear and uniform recording of observations provides a means to compare observations using uniform evaluation criteria, making it easier to assess severity of observed conditions and determine appropriate action.

As with any other bridge inspection, notes must include sufficient detail and description to be meaningful and useful for assessing, evaluating, and rating FRP deck components. As a minimum, the detailed description of observations should specifically include

- **Location of observed condition:** Reference the location from an easily identifiable point on the bridge. If possible, include a sketch to accompany the description and make the location easier to identify.

- **Extent (i.e., width, length, and depth) of the observed damage or condition:** Where possible, use sketches to complement the description of location and extent of observed condition.

- **Type of damage or observed condition:** This can include indications from visual, auditory, or any other type of inspection method. For example, conditions observed in a visual inspection could include discoloration, cracks, delaminations, deformation, signs of flow, and so forth. In acoustic or tap-test inspections, the types of conditions could include hollow, dead, or metallic sounds, etc.

- **Severity of observed condition or damage:** Although the level of severity is subjective, it should be based on a uniform scale. The severity scale or condition rating used should be the same for all other bridge components. One such scale is prescribed in FHWA's *Recording and Coding Guide for the Structures Inventory and Appraisal of the Nation's Bridges.* The scale from this publication, along with descriptive information of each point on the scale, has been modified and adapted for this manual. The scale is presented in Section 7.1.

- **Use standard nomenclature to define specific FRP deck elements and components as far as is practical.**
- **Note the likely cause of the observed condition or damage when and where possible.** When possible, also note the presence or absence of causal elements. In the case of cracks or other such damage, note whether such cracks or other defects are active (i.e., are affected by loading or environmental conditions).
- **Obtain photographs, audio recordings, videos, or other documentary evidence of the observed condition at the time of inspection.** The documentary evidence should be indexed with appropriate description and should be cross-correlated or cross-referenced in the field notes.

## 6.3 EVALUATION OF HISTORIC DATA

In all bridge inspections, observations and data from previous inspections are necessary to understand and assess changes in observed conditions on the bridge over time. In the case of FRP decks, the need for previous inspection data is even greater because FRP material may degrade and deteriorate more quickly than conventional construction materials. The heterogeneous nature of FRP and its likeliness to separate into its original constituent components necessitates watching for continuing degradation or defects.

Inspectors should carefully evaluate prior inspection findings before embarking on new inspections of FRP bridge decks. Specifically, the inspectors should review information on the following:

- The manufacturer, including all available quality assurance/quality control and manufacturer's inspection reports.
- Deck composition, material and manufacturing method used, and specific details of the deck construction.
- Observations noted during and immediately after construction.
- Any vehicular or other impact, fire damage, or chemical damage.
- The location, extent, and nature of previous damage or other significant observations.
- Progression of damage or deterioration, if any.

- The continued presence of causal elements.
- Information on any noticeable change in behavior of the deck due to observed condition or damage.
- The estimated path of damage progression and the likely effect if the damage is not controlled or mitigated.
- Descriptive specifics on the observed condition, such as color, gloss, density of cracks, warping, delamination, and so forth.

Study these items from all previous inspection reports, and check all the same locations identified in previous reports in the latest inspection to determine the progression of these conditions over time. Comparing the data from previous reports with observations in the latest inspection will help the inspector assess the condition's severity, the likely progression of damage, the condition's likely effect on deck behavior, and the urgency of alleviating any detrimental condition.

## 6.4 STANDARD CHECKLISTS

This section provides recommended checklists that could be used for inspection of FRP decks. Note that, in addition to the recommendations provided in this manual, the inspector must follow all safety regulations and practices as required for any bridge inspection.

### 6.4.1 PRE-INSPECTION CHECKLIST

Before embarking on fieldwork, make sure to have all the appropriate inspection equipment and other items needed to efficiently carry out the inspection work in the field. Such items should include

- All necessary personal safety equipment;
- Flashlight;
- Small mallet or hammer;
- Feeler gages;
- Tap tester;
- Camera;
- Notepad, pencils, etc.;
- FRP deck detail drawings;

- Manufacturer's specifications and other manufacturing information about the deck material and composition;
- Detailed drawings;
- Deck connection details and specifications for any adhesives used; and
- Material specifications for FRP deck.

### 6.4.2 CHECKLIST OF DETAILS AND ITEMS TO BE INSPECTED

The checklist of external details (deck structure) is as follows:

- Anchor holes/shear studs/connection clips;
- Supports, haunches, bearings, etc.;
- Curbs and curb connections to FRP deck;
- Parapets and railings and their connections to FRP decks;
- Scuppers, drainage holes, and other such areas on FRP decks;
- Approach joints;
- Panel-to-panel connections; and
- Wearing surfaces.

The checklist of internal details is as follows:

- Wearing surface, deck top facesheet;
- Deck bottom facesheet;
- Panel-to-panel joints;
- Web members; and
- Deck core.

### 6.4.3 FRP DAMAGE TYPES CHECKLIST

The evidence of FRP damage includes

- Blistering;

- Voids;
- Discoloration;
- Glossiness;
- Cracks;
- Delamination;
- Presence of moisture;
- Abrasion or tearing; and
- Creep, flow, or rupture.

### 6.4.4 INSPECTION AND TEST METHODS CHECKLIST

The inspection and test methods are as follows:

- Visual inspection and testing,
- Tap testing,
- Thermal testing,
- Acoustic testing,
- Ultrasonic testing,
- Radiography, and
- Modal-parameter analysis.

## 6.5 INSPECTION FORMS

Inspection summary forms are presented in Tables 6.5-1 through 6.5-4. These documents are intended to serve as organizers for FRP bridge deck inspectors' data. Their functional purpose is to organize field note data, sketches, photographs and other documentation into the inspection condition rating categories presented throughout this manual. The inspector is expected to use his or her notes and observations in conjunction with rating tables presented in Section 7 to assign condition ratings to FRP bridge decks.

## Table 6.5-1 Bridge, Deck, and Inspection Program Information

| | |
|---|---|
| **Bridge Number:** | **Inspection Date:** |
| **Bridge Name:** | **Inspection Type:** |
| **Bridge Location:** | **Year Built:** |
| **Feature Carried:** | |
| **Feature Under:** | |
| **Inspection Agency:** | |
| **Inspection Team (Circle Team Leader):** | |

| | | |
|---|---|---|
| Bridge Deck and Geometry | | |
| i. | Date FRP deck installed | |
| ii. | Structure type (S=simple span, C=continuous, etc.) | |
| iii. | Number of spans and span lengths | |
| iv. | Deck width | |
| v. | Deck manufacturer | |
| Cross Section and Geometry of the FRP Panels | | |
| i. | Panel length (ft) × width (ft) × depth (in.) | |
| ii. | Cross-section geometry (honeycomb, truss, other) | |
| iii. | Panel type (solid core, hollow core, etc.) | |
| Manufacturing Process | | |
| i. | Pultrusion | |
| ii. | Sandwich type hand-lay-up | |
| iii. | Vacuum infusion | |
| iv. | Other | |
| Type of Fiber and Resins | | |
| i. | E-Glass fiber | |
| ii. | Carbon fiber | |
| iii. | Epoxy resin | |
| iv. | Polyester resin | |
| v. | Vinylester resin | |
| Material Properties | | |
| i. | Shear strength | |
| ii. | Tensile strength | |
| iii. | Impact resistance | |

| Inspection/Damage Detection Methods Used | | Yes? | Detailed field note page reference | Instrument(s) used |
|---|---|---|---|---|
| i. | Visual inspection | | | |
| ii. | Tap test | | | |
| iii. | Thermal | | | |
| iv. | Acoustic | | | |
| v. | Ultrasonic | | | |
| vi. | Radiography | | | |
| vii. | Other | | | |

### Table 6.5-2 Inspection Summary Form – Internal and External Details

| | |
|---|---|
| **Bridge Number:** | **Inspection Date:** |
| **Bridge Name:** | **Inspection Type:** |
| **Bridge Location:** | **Year Built:** |
| **Feature Carried:** | |
| **Feature Under:** | |
| **Inspection Agency:** | |
| **Inspection Team (Circle Team Leader):** | |

| | | | | |
|---|---|---|---|---|
| **Inspection Summary for Deck Structure** | | | | |
| Types Observed | | Yes? | Detailed field note page reference | Is the damage active? (causal element exists) |
| i. | Cracks, holes | | | |
| ii. | Impact damage | | | |
| iii. | Abrasion or tearing | | | |
| iv. | Delamination | | | |
| v. | Creep/stress rupture | | | |
| vi. | Fatigue damage | | | |
| vii. | Moisture ingress/absorption | | | |
| viii. | UV or other weather-related damage | | | |
| ix. | Other (heat, freeze-thaw, etc.) | | | |
| Damage Types Observed | | Yes? | Detailed field note page reference | Is the damage active? (causal element exists) |
| i. | Cracks, holes | | | |
| ii. | Impact damage | | | |
| iii. | Abrasion or tearing | | | |
| iv. | Delamination | | | |
| v. | Creep/stress rupture | | | |
| vi. | Fatigue damage | | | |
| vii. | Moisture ingress/absorption | | | |
| viii. | UV or other weather-related damage | | | |
| ix. | Other (heat, freeze-thaw, etc.) | | | |

## Table 6.5-3 Inspection Summary Form for Connections and Joints

| | |
|---|---|
| **Bridge Number:** | **Inspection Date:** |
| **Bridge Name:** | **Inspection Type:** |
| **Bridge Location:** | **Year Built:** |
| **Feature Carried:** | |
| **Feature Under:** | |
| **Inspection Agency:** | |
| **Inspection Team (Circle Team Leader):** | |

**Inspection of Summary for Joints and Connections**

| | | Yes? | Detailed field note page reference | Is the damage active? (causal element exists) |
|---|---|---|---|---|
| **1. Anchorage/shear stud holes** | | | | |
| Hole condition | | | | |
| Fraying or other damage | | | | |
| Condition of concrete within hole | | | | |
| Any other signs of distress in and around the hole | | | | |
| **2. Clips and bolts at FRP deck to stringer connections** | | | | |
| Bolt/nut tightness | | | | |
| Evidence of movement of clips | | | | |
| Abrasion damage on FRP decks at clips | | | | |
| Cracked or damaged clips | | | | |
| **3. Shear studs, haunches, seating of deck on stringers** | | | | |
| Condition | | | | |
| Signs of separation of deck from seat | | | | |
| Signs of warping or other distress | | | | |
| **4. Panel-to-panel joints** | | | | |
| Joint type | | | | |
| Signs of movement | | | | |
| Presence of cracking | | | | |
| Elevation differences between panels | | | | |
| Wearing surface damaged over joint location | | | | |
| Water leakage through joints evident | | | | |
| **5. Approach transverse joints** | | | | |
| Spalling or scaling in approach pavement | | | | |
| Cracking in deck at approach joint | | | | |
| Settlement of approach pavement | | | | |
| Damage to wearing surface at joint | | | | |

## 6.5-4 Inspection Summary Form for Deck External Components

| | |
|---|---|
| **Bridge Number:** | **Inspection Date:** |
| **Bridge Name:** | **Inspection Type:** |
| **Bridge Location:** | **Year Built:** |
| **Feature Carried:** | |
| **Feature Under:** | |
| **Inspection Agency:** | |
| **Inspection Team (Circle Team Leader):** | |

**Inspection Summary for Deck Components**

| | | Yes? | Detailed field note page reference | Is the damage active? (causal element exists) |
|---|---|---|---|---|
| **1. Curbs/sidewalks** | | | | |
| Impact damage | | | | |
| Abrasive wear | | | | |
| Cracking | | | | |
| Scaling or spalling | | | | |
| **2. Parapets and guard rails** | | | | |
| Collision damage | | | | |
| Damage at connection to FRP | | | | |
| Coating failure | | | | |
| Loss of section | | | | |
| **3. Scupper areas** | | | | |
| Clogging of drain | | | | |
| Cracking of FRP damage | | | | |
| Impact damage | | | | |
| **4. Wearing surface** | | | | |
| Surface wear | | | | |
| Delaminations/disbands | | | | |
| Spalling/potholes | | | | |
| Abrasion/tearing | | | | |
| **5. Other** | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

# SECTION 7: CONDITION ASSESSMENT

This section provides procedures for condition assessment, evaluation, and rating of FRP deck conditions observed in the field.

## 7.1 CONDITION RATING OF FRP DECKS

The basis for rating condition of FRP bridge decks provided in this manual parallels contemporary inspection and rating practice for bridges constructed of traditional materials. With minor modifications accounting for differences in procedures among states, the condition-rating protocol defined in this document can generate ratings for integration with federal and state-specific rating procedures.

FHWA's *Recording and Coding Guide for the Structures Inventory and Appraisal of the Nation's Bridges* provides the uniform scale presented in Table 7.1-1 to rate the general condition of bridge components. This condition-rating scale was used as the guide for developing rating protocols for FRP bridge decks. Sections 7.1.1 through 7.1.3 of this manual provide condition-rating tables for FRP bridge deck components.

**Table 7.1-1 Bridge Condition Rating Table**

| Severity Level | Condition | Description |
|---|---|---|
| 9 | Excellent | Excellent condition, typically new construction. |
| 8 | Very Good | No problems noted. |
| 7 | Good | Some minor problems. |
| 6 | Satisfactory | Structural elements show some minor deterioration. |
| 5 | Fair | All primary structural elements are sound, but may have minor section loss, cracking, spalling or scour. |
| 4 | Poor | Advanced section loss, deterioration, spalling or scour. |
| 3 | Serious | Loss of section, deterioration, spalling or scour has seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present. |
| 2 | Critical | Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored, closing the bridge may be necessary until corrective action is taken. |
| 1 | Imminent Failure | Major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service. |
| 0 | Failed | Out of service—beyond corrective action. |

### 7.1.1 GUIDELINES FOR ASSESSMENT AND CONDITION RATING OF FRP DECKS

Tables are presented below for distilling inspection results from the inspection forms presented in Section 6.5 into deck element ratings. The tables and guidelines presented below are a qualitative measure for systematically translating the physical damage identified through inspection to a condition rating for the structure.

The inspector should be aware that these guidelines are based on limited national experience with condition rating of FRP bridge decks. As such, these will be subject to future changes and refinement. Finalizing representative and comprehensive guidelines will require more information to be generated from field and laboratory evaluation of FRP decks in the next decade.

The inspector is expected to thoughtfully review compiled condition data organized by categories presented in the tables of Section 6.5, and, quantifying the frequency and volume of distress observed in inspections, enter the condition rating tables of this section of the manual to derive a rating on the basis of comparisons with damage thresholds and observed conditions.

To categorize inspection observations relating various damage levels with the deck condition rating and damage severity levels listed in Table 7.1-1, deck details and corresponding specific damage types were divided into two categories. The first category, Deck Structure, encompasses important internal deck details (i.e., flanges and web elements) whose damage and deterioration will have direct influence on the structural integrity and safety of the deck and the highway bridge. The second group incorporates other features of the FRP deck, which are critical to function, rideability, durability, and maintenance planning for the bridge.

- **Group 1: Deck Structure.** This item rates internal and external deck details consisting of flanges, webs, and their connections and the structural condition of the deck. This condition rating reflects the overall condition rating and safety of the deck. Specific signs of damage known to affect these elements include
  - *Structural damage* including cracks (deep or through cracks perpendicular to FRP deck span), delaminations, and voids in FRP matrix, and
  - *Surface degradation* including cracking (shallow surface cracking or cracking parallel to FRP deck span), blistering, wrinkling, discoloration, scratches, and fiber exposure.
- **Group 2: Other Deck Features.** These include the following:
  - *Wearing surfaces or overlays*. Traffic surfaces degrade with time; establishing degree of wear attributable to normal traffic patterns or resulting from accidental overload, impact, vandalism and materials failure is necessary. Deterioration of wearing surfaces can include delamination, abrasive wear, tearing, cracking, and spalling.

- *Joints,* including panel-to-panel joints, panel-to-girder joints, and approach joints are rated. Deteriorating FRP deck joints can display separations and openings between elements, cracking and movement of joints, and damages to deck elements in the vicinity.
- *Railings.*
- *Curbs.*

Condition rating of elements in this latter group will not be used for deck evaluation; however, their condition should be noted in the inspection report.

It is noted that state DOT inspection practice commonly requires that bridge inspectors assess and note drainage conditions and characteristics of bridges and bridge decks, although ratings are not assigned for this element. The inspector can note in the section of Table 6.5-4 under the heading "Other" whether ponding of water on the deck surface or debris buildup on the deck or in the drains prevents water from draining.

The following section describes condition rating procedures for the deck structure. Section 7.1.3 provides the inspector tables to rate condition of other deck features.

### 7.1.2 CONDITION RATING OF THE FRP DECK STRUCTURE

Because of differences between the characteristics and structural behavior of FRP decks and those of other types of decks, the established damage thresholds and definitions cannot be used directly and without modification to rate the condition of FRP deck structures. Accordingly, an approach unique to FRP decks is adopted here for determining the damage thresholds and incorporating these into the rating tables. The approach considers the damage types common for this type of structure and takes into account the potential for damage progression. Damage such as cracks (shallow or deep, parallel or perpendicular to FRP panel span) and other surface degradations are assumed to have implications similar to those posed by comparable structural, functional, and durability damage in other common types of deck structures. Therefore, the thresholds for these types of damages, including their extent expressed in percentage of deck area, are extracted from established condition rating tables (e.g., *Michigan Structure Inventory and Appraisal Coding Guide*, Appendix B: Bridge Safety Inspection Report [BSIR] Rating Definitions, BIR 6).

For delaminations and voids within the FRP deck flanges and between flanges and web elements, however, the potential for damage progression unique to this type of structure becomes the determining factor. Evaluating the likelihood of progression of any type of damage within the FRP deck will require judgment based on damage metrics found within the FRP composites industry. Clearly, any level of damage is undesirable, but once damage is discovered, the specific decision to be made is whether it is severe enough to require immediate lane closure and repair or whether action can be delayed without threatening public safety or the deck's overall performance. As discussed in previous sections, the main load-carrying member of a sandwich panel is the top facesheet, which is continually subject to material stresses from direct traffic and impact loads. The top facesheet is the first structural element that will require scrutiny upon the discovery of any deterioration or signs of damage on the wear surface.

The two most significant damage conditions for the facesheet are (1) the separation of layers within in the facesheet, defined as a "delamination," and (2) the more severe case of full detachment of a facesheet section from the underlying core, referred to as a "debonded facesheet." These damage conditions may not be directly detectable during routine inspections unless their size is significant enough to produce a visible bulge on the top surface. The presence of noncritical damage to surrounding structural elements such as reflective cracking in the wear surface or local damage to joints may signal the initiation of delamination, so closer examination of the underlying facesheet would be necessary. If no visible signs of physical change are apparent in the facesheet, then further examination is not needed. If a physical change or anomaly is discovered, the inspector then has to determine whether the conditions indicate a delamination or debond.

A methodology, which is proposed to determine whether a delamination will likely progress if unattended, is described in detail in Appendix 9 of the report (the report is bound with this manual, see p. 124; the report's appendixes are published at trb.org/news/blurb_detail.asp?id=5905). Here, the results are considered to derive damage thresholds that can be incorporated directly into the condition rating tables. For simplicity, separation of layers in a facesheet and full detachment of a facesheet from the web core are considered and called "delamination" for rating purposes. The procedure is based on a simplified approach taken from the damage inspection of honeycomb sandwich panels in the aircraft industry. The methodology is not intended to be a rigorous examination of failure, but is an approximate approach to determine whether further failure is likely based on measurable size of delaminations.

Figure 7.1.2-1 represents critical delamination dimensions for a common 8-in.-deep FRP deck with spans of 4, 6, 8, and 10 ft using the analysis from Appendix 9 of the report. The chart was developed based on a HS25 wheel loading with an impact factor of 30%; different load and impact factor charts can be developed for alternate combinations. A safety factor of 3 is incorporated in this chart. Four curves illustrate the relationship between facesheet (flange) thickness and the critical delamination size for four span lengths. The critical delamination size is defined as a limiting defect dimension. Delaminations with defect dimensions less than or equal to the critical size will not propagate under the influence of HS25 loading.

The dashed lines show the flange thicknesses corresponding to each span length, assuming that the flange was designed originally for HS25 wheel load (ignoring dead load). With this assumption, the horizontal coordinate of the intersection between each dashed line with the corresponding curve for the same span length determines an approximate critical delamination size for that span length. The facesheet thickness required for a 4-ft to 10-ft span deck ranges from approximately 0.22 in. to 0.55 in. The corresponding critical delamination sizes vary from 6 in. to 15 in.

Therefore, for an 8-in.-deep FRP deck, depending on span of interest, a delamination size smaller than 6 in. to 15 in. in diameter can be tolerated without structural degradation.

For simplicity, if one limits the flange thickness to two sizes, say ¼ in. and ½ in., then the critical delamination size will be in the range of 8 in. to 14 in. This means that delamination sizes smaller than 8 in. will not have any structural consequences and those larger than 14 in. will have structural consequences, regardless of the flange thickness. This relationship was used in defining the damage thresholds in the deck structure rating table (Table 7.1.2-1). Accordingly, delamination sizes of 8 in. to 14 in. have been considered as thresholds for conditions from "fair" to "serious," respectively. The threshold for a "satisfactory" condition was assumed to be one-half of the lower bound of the critical delamination size—that is, 4 in. Also, it has been assumed that for a deck structure to be in its "critical" condition, an existing delamination will have had to progress to about 2 ft (24 in.). It is important for the inspector to recognize that the above thresholds are for an 8-in.-deep deck and incorporate other assumptions, so they may not apply to all cases. However, they represent an approximate and safe threshold for the purpose of inclusion in the rating tables.

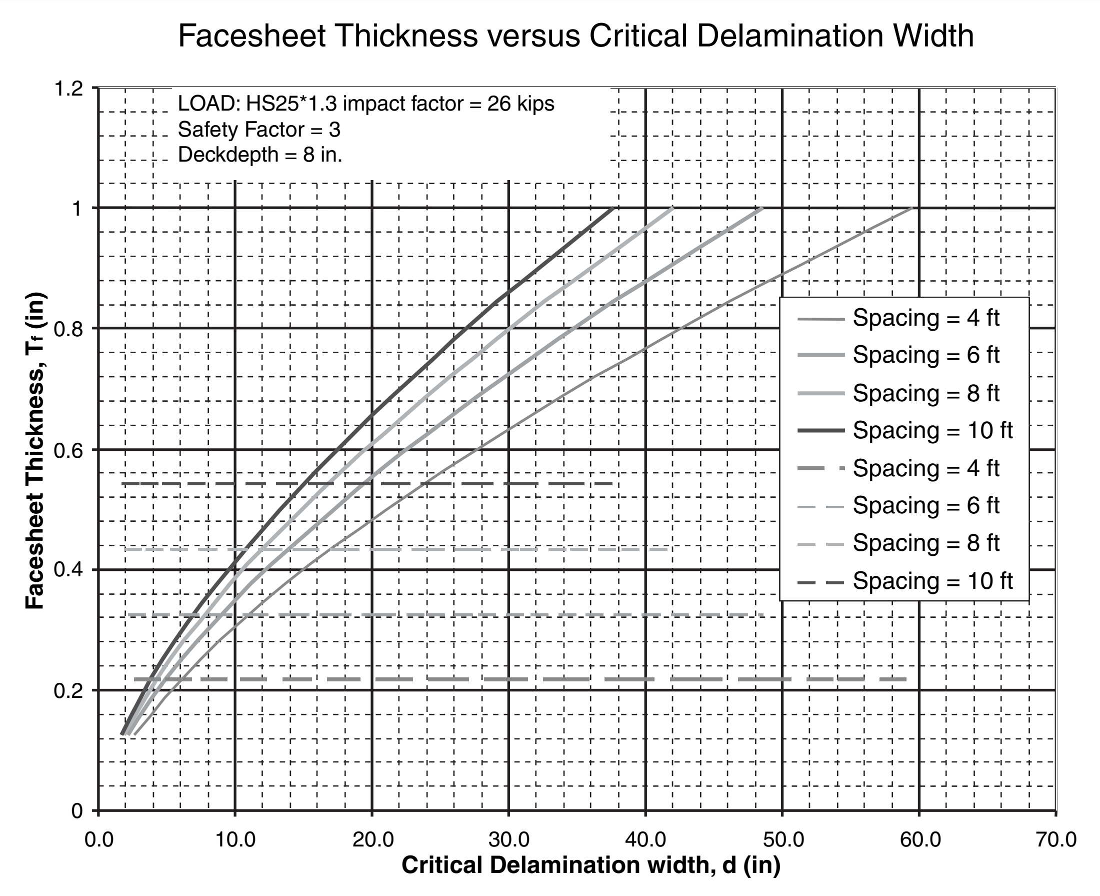


**Figure 7.1.2-1 Typical critical delamination sizes used for damage threshold derivations.**

The following table describes condition and damage thresholds corresponding with the nationally recognized severity levels in Table 7.1-1, based on the discussion above.

## Table 7.1.2-1 Condition Rating of FRP Deck Structure*

| Rating Code | Condition | Description |
|---|---|---|
| 9 | Excellent | Excellent condition, typically new construction. |
| 8 | Very Good | No significant problems noted. |
| 7 | Good | Minor surface damage in the form of hairline cracks in resin and scratches with no delamination evident on the deck surfaces or underneath. |
| 6 | Satisfactory | Minor damages in the form of shallow cracks in resin, scratches, blistering, abrasion and small delaminations over less than 2% of surface area total. Fibers are not exposed, ruptured, or buckled at the surface damage locations. Delamination smaller in every dimension than 4 in. and away from structural details or located such that structural function will not be impaired. |
| 5 | Fair | Damage in the form of shallow cracks in resin, scratches, blistering, abrasion, and small delamination extends over 2% to 10% of surface area total. Fibers exposed but not ruptured, buckled, or debonded at the surface damage locations. Delamination smaller in every dimension than 8 in. and located away from structural details or located not to have structural effects. Deck will function as designed. |
| 4 | Poor | Surface damage in the form of cracks in resin, scratches, blistering, abrasion, and delamination extends over 10% to 25% of area total. Fibers in the cracks exposed but not debonded, buckled, or ruptured at the surface damage locations. Delamination smaller in every dimension than 8 in. but near structural details or located to have structural effects. Deck will function as designed, but functionality may be impaired without repairs. |
| 3 | Serious | Surface damage in the form of deep cracks in resin, scratches, blistering, abrasion, and delamination extends over more than 25% of area total. Fibers are visibly exposed and debonded, but not ruptured or buckled at the surface damage locations. Delamination smaller in every dimension than 14 in. Structural analysis may be necessary to determine whether the deck can continue to function without restricted loading. |
| 2 | Critical | Fibers are exposed, debonded, and ruptured, or buckled at the surface damage locations. Delamination larger in any dimension than 24 in. Unless closely monitored or posted for reduced loads, closing the bridge may be necessary until corrective action is taken. |
| 1 | Imminent Failure | Major deterioration or damage present; large delaminations, cracks or voids, punctures, major fiber rupture, or buckling through cracks perpendicular to the FRP panel span, sag, or dislocation visible; large, and inconsistent deflections under traffic observed. Bridge is closed to traffic but corrective action may put back in service. |
| 0 | Failed | Out of service—beyond corrective action / deck must be replaced. |

*Note: Use Table 7.1.3-1 to rate wearing surface.

### 7.1.3 CONDITION RATING OF OTHER DECK FEATURES

As described earlier, condition ratings of other deck features are to be noted in the inspection report.

State inspection practice commonly requires that bridge inspectors assess and note drainage conditions and characteristics of bridges and bridge decks, although ratings are not assigned for this element. The inspector can note in the section of Table 6.5-4 under the heading "Other" whether ponding of water on the deck surface exists or debris buildup on the deck or in the drains prevents water from draining.

Tables 7.1.3-1 through 7.1.3-4 describe condition and damage thresholds corresponding to the nationally recognized severity levels in Table 7.1-1. These tables follow the general format and include applicable thresholds from tables with the same titles from established condition rating manuals (e.g., *Michigan Structure Inventory and Appraisal Coding Guide*, Appendix B: Bridge Safety Inspection Report [BSIR] Rating Definitions, BIR 1 and Item 58A for wearing surface, BIR 2 and BIT 3 for joints, BIR 4 for railing, and BIT 5 for curbs and sidewalks). Modifications, customization and additions have been applied to fit the FRP decks under consideration.

**Table 7.1.3-1 Condition Rating of Wearing Surface**

| Rating Code | Condition | Description |
|---|---|---|
| 9 | Excellent | Excellent condition, typically new construction. |
| 8 | Very Good | No significant problems noted. |
| 7 | Good | Light surface wear observed. |
| 6 | Satisfactory | Surface area exhibits 2% or less of delaminated, disbonded, or worn areas, including repaired areas. |
| 5 | Fair | Between 2% and 10% of the surface area is worn, disbonded, or delaminated. There may be excessive cracking in the surface. Heavy abrasive wear of membrane overlays or potholes in bituminous overlays are present. This includes repaired areas and/or areas in need of corrective action. |
| 4 | Poor | Large areas of the surface, 10% to 25% are worn, cracked, disbonded, or delaminated. This area includes repaired areas and/or areas in need of corrective action. |
| 3 | Serious | More than 25% of the surface area is affected by wearing surface degradation and delaminations/disbonds. These areas include repaired areas and/or areas in need of corrective action. |
| 2 | Critical | Emergency surface repairs required. |
| 1 | Imminent Failure | Bridge is closed to traffic but corrective action may put back in service. |
| 0 | Failed | Bridge closed. |

## Table 7.1.3-2 Condition Rating of Joints

| Rating Code | Condition | Description |
|---|---|---|
| 9 | Excellent | Excellent condition, typically new construction. |
| 8 | Very Good | No problems noted. |
| 7 | Good | Minor deterioration with hairline cracks less than 1/32 in. (0.8 mm). No noticeable water leakage observed from underside. |
| 6 | Satisfactory | Minor deterioration with shallow hairline cracks greater than 1/32 in. (0.8 mm) and shallow spalls/delamination within 2 ft of the joint. No noticeable water leakage. |
| 5 | Fair | Evidence of joint degradation visible due to cracking in overlay or topping above panel joint locations. Gaps and cracks of up to 1/16 in. width over 10% of length; no loss of bolts, clips or other devices. Signs of water leakage through joints present. |
| 4 | Poor | Gaps and cracks of up to 1/4 in. over 20% of length, few clips or bolts loose or lost, elevation changes for adjacent panels evident, crack movement observed with passing traffic loads. Widespread signs of water leakage through joints. |
| 3 | Serious | Gaps and cracks of up to 1/2 in. over 30% of length, 5% of clips or bolts loose or lost, elevation changes for adjacent panels, noticeable differential vertical or horizontal movement of the adjacent panels in traffic. |
| 2 | Critical | Gaps and cracks wider than 1 in. and/or over 50% of length, 20% of clips or bolts loose or lost, large elevation differences between adjacent panels evident. Wearing surface extensively degraded in joint locations. Closing the bridge necessary unless emergency repairs are made. |
| 1 | Imminent Failure | Bridge is closed to traffic but corrective action may put back in service. |
| 0 | Failed | Bridge closed. |

### Table 7.1.3-3 Condition Rating of Railings

| Rating Code | Condition | Description |
|---|---|---|
| 9 | Excellent | Excellent condition, typically new construction. |
| 8 | Very Good | Small and superficial wear, deterioration, or collision damage. |
| 7 | Good | Minor deterioration with shallow hairline cracks in concrete components less than 1/32 in. (0.8 mm) or shallow scaling. Failure of paint or galvanizing on coated steel is very small and in scattered locations. Collision damage limited to minor scrapes. |
| 6 | Satisfactory | Minor deterioration with shallow hairline cracks in concrete components greater than 1/32 in. (0.8 mm) and shallow spalls or scaling limited to less than 2% of the surface area. Failure of the coating on steel components is limited to less than 2% of the surface area with no loss of section. Collision damage limited to minor scrapes. No noticeable damage to railing connection to the FRP deck. |
| 5 | Fair | Moderate deterioration with cracks in concrete components and spalls or scaling limited to less than 5 % of the surface area. Failure of the coating on steel components is limited to less than 5% of the surface area with minor loss of section. Collision damage limited to minor scrapes or temporary repairs in place. |
| 4 | Poor | Major deterioration with cracks in concrete components and spalls or scaling greater than 5% of the surface area. Failure of coating on steel components is greater than 5% of the surface area with some loss of section. Some collision damage but not affecting the performance of the railing. Minor damages to the railing connection to FRP deck. Temporary repairs may be in place. |
| 3 | Serious | Most of the railing components exhibit deterioration and/or loss of section. Collision damage and deterioration has not progressed to the point where the railing will fail if impacted. Minor damage to the railing connection to FRP deck. |
| 2 | Critical | Most of the railing components exhibit deterioration and/or loss of section. Collision damage and deterioration has progressed to the point where the railing may fail if impacted. Damages to the railing connection to FRP deck and to FRP material in the vicinity of connection. Immediate repairs are called for. |
| 1 | Imminent Failure | Lane or shoulder closed to traffic and temporary concrete barricades in place to keep the bridge open. Corrective action may put the bridge back in service. |
| 0 | Failed | Bridge closed. |

**Table 7.1.3-4 Condition Rating of Curbs and Sidewalks**

| Rating Code | Condition | Description |
|---|---|---|
| 9 | Excellent | Excellent condition, typically new construction. |
| 8 | Very Good | Minor cracking less than 1/32 in. wide (0.8 mm) with no spalling, scaling, or delamination. |
| 7 | Good | Open cracks less than 1/16 in. wide (1.6 mm) at a spacing of 10 ft or more, light shallow scaling allowed. |
| 6 | Satisfactory | Surface has considerable number of open cracks greater than 1/16 in. wide (1.6 mm) at a spacing of 5 ft or less. Surface area exhibits 2% or less of spalled or delaminated areas, including repaired areas. Medium scaling on the surface is 1/4 in. to 1/2 in. (6.4 mm to 13 mm) in depth. |
| 5 | Fair | Between 2% and 10% of the surface area is spalled or delaminated. There can be excessive cracking in the surface. Heavy scaling 1/2 in. to 1 in. in depth (13 mm to 26 mm) can be present. This includes repaired areas and/or areas in need of corrective action. |
| 4 | Poor | Large areas of the surface, 10% to 25%, are spalled or delaminated. This includes repaired areas and/or areas in need of corrective action. Spalls and scaling are not deep. |
| 3 | Serious | More than 25% of the surface area is spalled. This area includes repaired areas and/or areas in need of corrective action. Spalls and scaling are not deep. |
| 2 | Critical | Emergency surface repairs required by the crews. |
| 1 | Imminent Failure | Sidewalk or shoulder is closed, but corrective action may put it back in service. |
| 0 | Failed | Bridge closed. |

## 7.2 CORRELATION OF DAMAGE TO LIKELY CAUSES

This section provides guidance on how to relate a field-observed defect or damage to the types of loading or external condition that might have caused it. Adverse effects of loading often can be observed from visual evidence. The visual evidence typically consists of surface conditions such as chalking (ASTM D4214-89); checking (ASTM D660-93); cracking (ASTM D661-93); blistering (ASTM D714-94); and flaking (ASTM D772-86). In addition, FRP surface material can exhibit discoloration and loss of gloss (reflectivity) as a result of damage from exposure to radiation, chemicals, or fire. All these visual clues provide a means for the inspector to identify and isolate potential damage and its probable cause.

### 7.2.1 EFFECTS OF VEHICULAR LOADS

Evidence of the effects of vehicular loads can be divided into two distinct categories: (1) damage due to normal vehicular traffic over the bridge and (2) the damage due to accidental vehicle or vehicle-induced impact.

#### 7.2.1.1 Effects of Normal Vehicular Traffic

Damage due to normal vehicular traffic primarily affects the wearing surface and, to a limited extent, the panel joints and approach joints. Any damage from normal vehicular traffic would entail wear and tear of the wearing surface and potential abrasion at joints where components can move relative to each other. Visible signs of normal vehicular traffic–induced damage typically include

- Ruts or tire marks on the wearing surface;
- Map cracks or minor surface indentations on the wearing surface;
- Appearance of abrasion at panel joints, deck-to-stringer joints and clips, approach joints, the interface of curbs and decks, and the interface of parapets/railings and the deck; and
- Discoloration or loss of gloss on FRP surfaces.

#### 7.2.1.2 Effect of Vehicle or Vehicle-Induced Impact

Damage due to vehicular impact can typically occur at the curbs, parapets, approach guardrails, and approach joints. In addition, impact damage due to debris and rock hits as a result of vehicular motion can occur at other parts of the FRP decks. Such impact, if strong enough, will typically cause FRP material to indent and crack at the point of contact. Discoloration or loss of surface gloss may also be visible at and near the impact location. In addition, if the force of impact is sufficiently high, reflective cracking around the impact point may also be observed. The impact damage will typically be superficial, but in some cases, could penetrate the full depth of the FRP skin. Depending on the particular impacted component and the location of vehicular impact, there possibly could be additional indirect damage to other components in the vicinity of the impact.

### 7.2.2 EFFECT OF PUNCHING LOADS

FRP material, and particularly FRP decks, have high tensile strength as compared with conventional bridge materials such as steel and concrete. Laboratory testing has shown that this higher tensile strength makes FRP decks unlikely to fail or be damaged due to purely bending stresses. However, FRP deck components such as facesheets or wearing surfaces are relatively weak under directly applied loads. Therefore, heavy loads (high load per unit area) directly applied to FRP decks could in certain circumstances cause punching-type failures of FRP deck surfaces. In this type of failure, the deck surfaces or facesheets will punch through by failing around the perimeter of the applied load, shearing off the FRP material directly beneath the applied load.

## 7.2.3 EFFECT OF ENVIRONMENTAL AND OTHER LOADS

Environmental loads (e.g., temperature, radiation, and moisture), abrasive or damaging materials, and factors such as chemicals and fire can have significant adverse effects on FRP material. Some of these effects and conditions are discussed in the following sections.

### 7.2.3.1 Thermal

FRP composites are subjected to thermal cycles both during processing and throughout their service life. Process-related effects, in conjunction with in-service thermal exposure, can have a significant effect on the overall response and durability of a composite structure or component.

In-service thermal effects include

- High temperature effects (i.e., temperatures above the cure temperature);
- Low temperature effects; and
- Temperature variations, cycles, and freeze-thaw effects.

#### *7.2.3.1.1 High Temperature Effects*

Exposure to elevated temperature after manufacturing often can be advantageous by helping to post-cure composite. However, prolonged exposure to elevated temperatures can degrade composites due to differing thermal expansion coefficients and elastic properties between constituents. The long-term effects of elevated temperature are still relatively unknown, and this area has been highlighted for further research. Typical evidence of high temperature effects on composites includes the loss of gloss or color and the presence of blistering and air bubbles.

#### *7.2.3.1.2 Low Temperature Effects*

Due to the difference in coefficient of thermal expansion, a decrease in temperature causes the matrix to shrink relative to the fibers. Relatively stiff fibers with a lower thermal expansion coefficient resist this shrinkage, and residual stresses arise in the material microstructure. Large temperature differentials can cause microcracking in the material. This microcracking can contribute to material degradation by reducing stiffness and increasing permeability and water ingress through the fiber/matrix interface. However, except for severely cold environments, the induced stresses are of little concern. Low temperature effects are typically evidenced by the presence of microcracks on FRP surfaces.

#### *7.2.3.1.3 Freeze-Thaw Effects*

Within the normal temperature range, freeze-thaw typically has little effect on low-void-ratio composites, since a low void content keeps frozen moisture from being absorbed by the FRP and causing any appreciable damage. However, even with a low void ratio, severe thermal cycling can cause microcracks to form and grow. These microcracks can coalesce to form matrix cracks, leading to degradation of stiffness and other matrix-dominated properties.

### 7.2.3.2 Radiation

The effect of UV radiation on FRP composites is well documented from extensive research and testing undertaken in the defense and aerospace fields. Solar ultraviolet radiation has been shown to be deleterious to organic materials, and polymers are thus greatly affected by exposure to UV radiation.

However, the effects of UV exposure are generally reduced by applying UV-resistant coatings or similar treatments to exposed FRP surfaces. Light-stable resins and pigments have also been developed to further enhance the long-term stability of FRP composite structures exposed to radiation. Radiation typically affects only the top few microns of the exposed surface. Therefore, the UV degradation effect on structural properties of thicker sections is not as critical as on thin sections. However, the effects of temperature, moisture, wind-borne abrasives, and other environmental conditions complicate the influence of radiation and, despite radiation protection, could adversely affect FRP components.

Visual evidence of radiation-related damage can be observed on FRP surfaces exposed to solar radiation. Prolonged exposure of FRP material to sunlight typically results in hardening of the matrix, as well as color change or loss of pigment. Loss of gloss and luster and surface discoloration are signs that indicate potential radiation damage of FRP.

### 7.2.3.3 Chemicals

Chemicals, especially alkaline solutions, can degrade the main constituents of FRP composites. This is particularly true of bare glass fibers, where a reaction with an alkaline solution forms expansive silica gels. However, the composite system as a whole can be designed to provide superior chemical resistance by selecting appropriate constituent materials and resins. The typical visual signs of damage due to chemicals include discoloration and blistering.

### 7.2.3.4 Moisture

The effect of moisture depends on characteristics of the material and other environmental conditions such as temperature. Temperature influences the quantity, distribution, and rate of water absorption into the composite material. As temperature increases, the amount and rate increase rapidly. In some cases, water accumulated at the fiber/matrix interface contributes substantially to the shear strength loss of the material. It has also been shown that ingress of water through voids in a composite can cause the resin to plasticize. Absorption of water by FRP and freeze-thaw cycles thereafter can result in freeze-thaw-initiated damage of FRP decks. Visible signs of moisture ingress in the composite could be bulging and swelling of composite surfaces and, in some extreme cases, the visible presence of water.

#### 7.2.3.5 Fire

The resin component of most FRP is undoubtedly combustible, and as this forms a significant proportion of the material, it must be taken seriously in any consideration of fire. Different resins exhibit various characteristics, and a number of retarding low-smoke additives are available to customize fire response still further. However, fire can damage the resin, resulting in loss of composite action between the fibers and resin and a subsequent loss in FRP strength. In addition, the matrix can ignite and release potentially harmful toxic smoke. Signs of fire damage range from char and burn marks to signs of melted resins, warping of FRP sections, and blistering. Loss of color and gloss also typically accompany fire damage.

### 7.2.4 OTHER EFFECTS

Other loads that can have significant effect on long-term behavior of FRP decks include creep and fatigue.

#### 7.2.4.1 Creep

Creep is the permanent deflection of a material under long-term loading. Like most conventional construction materials, FRP composites are prone to creep under sustained loading. However, virtually all creep comes from the visco-elastic behavior of the polymer resin and very little from the glass reinforcements. Thus, creep would exist mainly in load conditions that would impart high and sustained shear or compression forces on the section of composite material with high resin content. Because creep is a resin-dependent phenomenon, the amount of creep depends on temperature and operating environment. For example, FRP materials demonstrate higher creep levels at higher temperatures and also higher creep levels when submerged in liquid rather than in air. Typically, maintaining stresses below appropriate working stress levels controls creep. There are no specific visual signs of creep. However, creep can be assessed by monitoring and comparing deck deflection over a period of time.

#### 7.2.4.2 Fatigue

Fatigue characteristics represent the response of a material to cyclic loading. Repeated cyclic loading usually results in a decrease in strength properties of the material. Limited research is available on fatigue behavior of FRP decks. However, cyclic loading data from FRP specimens for wind turbine blades showed cycles to failure stabilizing past $1x10^6$ at 33% of laminate ultimate stress under tension/compression reverse cycles and past $1x10^7$ at 50% of ultimate stress under tension/tension loading. These tests were performed under full cyclic compression/tension cycles, so the results represent the worst-case fatigue condition. In most cases, the sections of FRP decks would be subjected to zero-tension or zero-compression cycles due to the on-and-off nature of traffic loads, so fatigue conditions would be far less severe. Consequently, one can expect the strength to stabilize at cycles less than the indicated cycles to failure under full compression/tension conditions. In addition, deflection/stiffness governs the design of FRP decks in most cases and they are typically designed with a high factor of safety (2.5 or more) so that the working stresses typically fall well under 50% of material strength. This presents a significant advantage over concrete, for example, in terms of tensile load capacity.

## 7.3 EVALUATION OF CONTINUED EXISTENCE OF CAUSAL ELEMENTS

An inspector must be able not only to detect the defect or distress and its likely causal element, but also to ascertain whether the causal element continues to exist on the bridge. The inspector should make every attempt first to identify the causal element and, second, to assess whether the causal element continues to exist. If the causal element continues to exist, then the inspector should flag the observation, requesting immediate action to remove or mitigate the causal element.

## 7.4 REFERENCE

1. Bach, P. "High Cycle Fatigue of Glass Fibre Reinforced Polyester," *Proceedings of IEA Workshop on Fatigue in Wind Turbines*, ETSU, Harwell, 1988.

# SECTION 8: CASE STUDY OF THE SALEM AVENUE BRIDGE

The Salem Avenue Project (1999) was an ambitious project to use FRP composite decks on an existing State Route 49 bridge spanning the Great Miami River just west of downtown Dayton, Ohio. Four deck manufacturers provided FRP decks to the project. Decks from the first three manufacturers are discussed in here. The fourth supplier's deck system is a hybrid FRP/concrete deck, so it is excluded from discussion. In summary, functional problems started developing on all four deck systems shortly after the bridge was reopened to traffic. The problems became severe enough that repairs were attempted and lanes were closed until the problems could be resolved. An investigation team formed in mid-2000 thoroughly inspected the bridge and deck work and then conducted interviews with every manufacturer, contractor, and agency involved.

The team identified design integration, maintenance, and serviceability problems, including the following:

- Delaminations and unbonded areas in panel skins,
- Deck-to-girder connection at haunches,
- Field and shop joint problems,
- Polymer wear surface deficiencies,
- Joint incompatibility between different deck systems, and
- Water intrusion.

Remedies were developed and recommended for each of the issues. Many were correctable on-site, but some deficiencies stemming from manufacturing flaws and installation quality-control problems required manufacturer intervention and repair. In the end, Ohio DOT decided the cost of repair and downtime would be too high and chose instead to remove the damaged decks.

Some examples of detectable problems seen during inspection of the decks are presented in Figures 8-1 through 8-10.

**Figure 8-1 Walk-through inspection on Salem Bridge; wear surface cracking and spalling observed.**

**Figure 8-2 Wear surface lift on deck.**

**Figure 8-3 Observed blister location on deck.**

**Figure 8-4 Water spouting out of drill holes on deck.**

**Figure 8-5  Haunch inspection shows deck rise.**

**Figure 8-6  Tap tests indicate debonding of facesheet.**

Figure 8-7 Coring through deck.

Figure 8-8 No adhesive between facesheet and core webs.

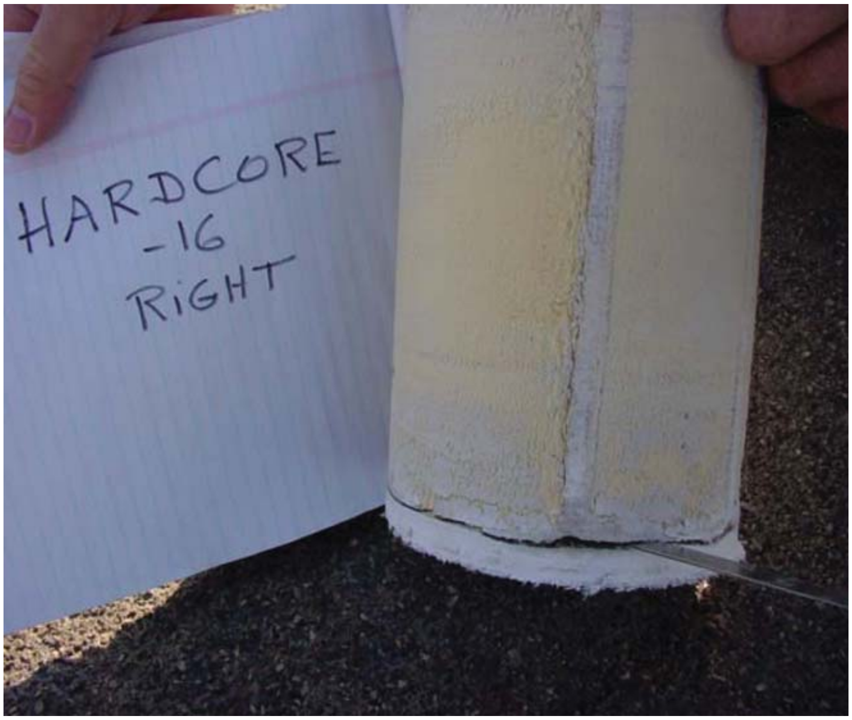


**Figure 8-9 Coring of deck reveals detached facesheet.**

**Figure 8-10 Water accumulation in cavity of deck.**

# GLOSSARY OF COMMON COMPOSITES INDUSTRY TERMS

**Adhesive** – Substance capable of holding materials together by surface attachment. Adhesive types include a monomer of at least one of the polymers to be joined, catalyzed to produce a bond by polymerization; solvent cement that dissolves the plastics being joined, forming strong intermolecular bonds, and then evaporates; bonded adhesives or solvent solutions of resins, sometimes containing plasticizers, which dry at room temperature; and reactive adhesives or those containing partially polymerized resins (e.g., epoxies, polyesters, or phenolics), which cure with the aid of catalysts to form a bond.

**ASNT** – American Society of Nondestructive Testing.

**Balanced laminate** – A composite laminate in which all laminae at angles other than 0° and 90° occur only in plus or minus pairs (not necessarily adjacent) and are symmetrical about a centerline.

**Barcol hardness** – Value obtained by measuring the resistance to penetration of a sharp, spring-loaded steel point. The value can be used as a measure of the degree of cure of a plastic.

**Blemish** – Any surface imperfection of a coating or substrate.

**Blistering** – A localized swelling and separation between any of the layers of a laminate.

**Calcium carbonate** – Used as fillers for plastics. They are obtained from naturally occurring deposits as well as by chemical precipitation. The natural material is derived from natural chalk, limestone or dolomite, consisting of calcium carbonate with up to about 44% magnesium carbonate.

**Carbon fibers** – A group of fibrous materials essentially composed of elemental carbon. They may be prepared by pyrolysis of organic fibers, the most widely used method. Carbon and graphite fibers are used interchangeably. Graphite fibers are the stiffest fibers known and have very high strengths and moduli that remain constant at high temperatures. The higher the graphite content, the stiffer the fiber, but the lower the strength. Less expensive pitch-based fibers are an alternative to graphite fibers.

**CFRP** – Carbon-fiber reinforced plastic, a general term covering any type of plastic reinforced cloth, mat, strands, or any other form of fibrous glass.

**Chop strand** – A type of glass fiber reinforcement consisting of strands of individual glass fibers that have been chopped into short lengths and bonded together within the strands so that they remain in bundles after chopping.

**Clay filler** – Naturally occurring sediments rich in hydrated silicates of aluminum, predominating in particles of colloidal or near-colloidal size. Those of particular interest to the plastics industry such as kaolin or china clay are used as fillers in epoxy and polyester resins.

**Cocure** – The process of curing several different materials in a single step. Examples include the curing of various prepregs to produce hybrids or the curing of composite materials and structural adhesives to produce sandwich structure or skins with integrally molded fittings.

**Coefficient of thermal expansion (CTE)** – The fractional change in length (or sometimes in volume, when specified) of a material for a unit change in temperature.

**Composite material** – A material, usually manmade, that is a three-dimensional combination of at least two chemically distinct materials with a distinct interface separating the components, created to obtain properties that cannot be achieved by any of the components acting alone.

**Continuous mat** – Reinforcement fabric made with continuous fiber strands randomly bonded to form a flat sheet.

**Core** – The central member of a laminate to which the faces of the sandwich are attached.

**Cross-linking** – The establishing of chemical links between the molecular chains in polymers. When extensive, as in most thermosetting resins, cross-linking makes one infusible super-molecule of all the chains forming a three-dimensional or network polymer, generally by covalent bonding. Thermosetting materials cross-link under the influence of heat and/or catalysis, irradiation with high-energy electron beams, or chemical cross-linking agents, such as organic peroxides.

**Cure time** – The period of time during which a part is subjected to heat and/or pressure to cure the resin.

**Debond** – An area of separation within or between plies in a laminate or within a bonded joint, which can be caused by improper adhesion during processing, contamination, or damaging interlaminar stresses.

**Debulk** – The compacting or squeezing out of air and volatiles between plies or prepreg laminates under moderate heat and vacuum to ensure seating on the tool, to prevent wrinkles, and to promote adhesion.

**Delaminate** – To separate existing layers or split a laminated plastic material along the plane of its layers. It is the resultant effect of physical separation or loss of bond between laminate plies through failure of the adhesive.

**Dry spot** – An area of a reinforced plastic article that has (1) an insufficient amount of resin to wet out the reinforcement completely or (2) a lack of bonding between the reinforcement and the resin. This lack is evidenced by low gloss, dry spots or fiber-show. The condition may be caused by improper wetting or impregnation or by excessive molding pressure.

**E-glass** – A low alkali borosilicate glass with good electrical and mechanical properties and good chemical resistance. This type of glass is the most widely used in fibers for reinforcing plastics. Its high resistivity makes E-glass suitable for electrical laminates. The designation "E" is for electrical.

**Epoxy resins** – A family of thermosetting resins that were originally made by condensing epichlorohydrin and bisphenol A. Epoxy resins are now more generally formed from low molecular weight diglicidyl ethers of bisphenol A. Depending on molecular weight, the resins range from liquids to solid resins and can be cured with amines, polyamides, anhydrides or other catalysts. The solid resins are often modified with other resins and unsaturated fatty acids. Epoxy resins are also widely used in the reinforced plastics field because they have good adhesion to glass fibers and in electrical composites because their thermal expansion can be tailored to match that of copper. In addition, their low viscosities are effective in wetting various reinforcing materials.

**Exotherm** – The temperature/time curve of a chemical reaction giving off heat, particularly the polymerization of casting resins.

**Fabric** – A material constructed of interlaced yarns, fibers, or filaments, usually a planar structure. Nonwovens are sometimes included in this classification.

**Failure, adhesive** – The rupture of an adhesive bond such that the plane of separation appears to be at the adhesive-adherend surface.

**Failure, cohesive** – The rupture of an adhesive bond such that the separation appears to be within the adhesive.

**Fiber** – A single homogeneous strand of material having a length of at least 5 mm, which can be spun into a yarn or roving or made into a fabric by interlacing in a variety of methods.

**Fiber content (volume)** – The volume percent of fiber within a cured laminate as determined by analysis. This is compared with the resin volume.

**Fiber glass** – An individual filament made by mechanically drawing molten glass. A continuous filament is a glass fiber of great or indefinite length.

**Fiber orientation** – Fiber alignment in a nonwoven or mat laminate where the majority of fibers are in the same direction, resulting in a higher strength in that direction.

**Filament** – A variety of fibers characterized by extreme length such that there are normally no filament ends within a part except at geometric discontinuities. Filaments can be formed into yarn without twist or with very low twist. Used in filament winding processes and in filamentary composites that require long continuous strands.

**Foam** – Composite foams include syntactic and other foams such as graphite-urethane. Thermoplastic foams are also available for molding large parts: rigid foams are useful as core materials for sandwich construction.

**FRP** – Fibrous-glass reinforced plastic, a general term covering any type of plastic reinforced cloth, mat, strands, or any other form of fibrous glass.

**Gel time –** Time for conversion of a liquid to a gel state. The point in the curing cycle at which a dramatic increase in viscosity occurs due to initial network formation.

**Gelcoat** – (1) A quick-setting resin used in molding processes to provide an improved surface for the composite. (2) The first resin applied to the mold after the mold-release agent, which becomes an integral part of the finished laminate and is usually used to improve surface appearance. (3) High-build, chemical-resistant, thixotropic polyester coating.

**GFRP** – Glass fiber reinforced plastic.

**Glass cloth** – Conventionally woven glass fiber material.

**Glass fiber reinforcement** – A family of reinforcing materials for reinforced plastics based on single filaments of glass ranging in diameter from 3 to 19 micrometers (0.00012 in. to 0.00075 in.).

**Glass mat** – A thin mat of glass fibers with or without a binder.

**Graphite fibers** – See Carbon fibers.

**Honeycomb** – A manufactured product consisting of resin-impregnated sheet material (paper, glass fabric, etc.) or sheet metal, formed into hexagonal-shaped cells. Used as a core material and bonded with face sheets in a sandwich construction. The core is assumed to have no stiffness in the plane of the sandwich panel and infinite stiffness normal to the panel.

**Hygoscopic** – Having the tendency to absorb moisture from the air. Some resins are hygroscopic, thus requiring drying before molding.

**Interlaminar anomaly** – Descriptive term pertaining to some object (a void), event (a fracture), or potential field (a shear stress) referenced as existing or occurring between two or more adjacent laminae.

**Laminate** – A product made by bonding together two or more layers or laminae of material. In the reinforced plastics industry, the term refers mainly to superimposed layers of resin-impregnated or resin-coated fabrics or fibrous reinforcements that have been bonded together, usually by heat and pressure, to form a single piece.

**Laminate, angle-ply** – Consists of an arbitrary number of layers identical in thickness and material and having alternating directions $+x$ and $-x$.

**Laminate, cross-ply** – Consists of an arbitrary number of layers of the same material and thickness but with alternating orientations of 0° and 90°. This bidirectional laminate is orthotropic and has a Poisson's ratio of nearly 0.

**Laminate, isotropic** – A laminate in which the strength properties are equal in all directions.

**Laminate, orthotropic** – A ply geometry of laminate that must be arranged so that the gross in-plane elastic properties of the laminate possess three mutually perpendicular planes of symmetry parallel respectively to the sides of the specimen.

**Laminate, symmetric** – A stacking sequence of plies below the laminate midplane that must be a mirror image of the stacking sequence above the midplane.

**Layup** – (1) A process of fabrication that involves the stacking of plies of material in a specified orientation and sequence. (2) As used in reinforced plastics, the process of placing the reinforcing material in position in the mold or the resin-impregnated reinforcement. (3) A description of the component materials, geometry, and so forth, of a laminate.

**Mandrel** – A form around which pultruded and filament-wound structures are shaped or used for the base in the production of a part by lay-up or filament winding.

**Mat** – A fibrous material for reinforced plastic consisting of randomly oriented chopped filaments or swirled filaments with a binder cut to the contour of a mold, for use in reinforced plastics processes such as matched-die molding and hand lay-up or contact pressure molding.

**Matrix** – As applied to polymer matrix materials, it is the resinous phase of a reinforced plastic material in which the fibers or filaments of a composite are embedded.

**MEKP** – Abbreviation for Methyl Ethyl Ketone Peroxide, a curing agent for polyester resins.

**Modulus of Elasticity** – The ratio of stress (nominal) to corresponding strain below the proportional limit of a material. It is expressed in force per unit area, usually pounds per square inch or kilograms-force per square centimeter.

**Modulus of Rupture** – The force necessary to break a flexure specimen of specified width and thickness in bending expressed in pounds-force per square inch.

**Modulus, Young's** – Modulus of Elasticity.

**NDE** – Nondestructive evaluation.

**NDI –** Nondestructive inspection.

**NDT –** Nondestructive testing.

**Orientation angle –** The relative angle of the warp direction in a fabric to the chosen zero direction shown on the face of the drawing. It would probably be the yarn or tow direction in a unidirectional tape.

**Outgassing –** The evolution of embedded gas from a material by heat.

**Peeling –** The detachment of one layer from another because of poor adherence.

**Ply –** As applied to laminates, the layers of fiber or reinforcements.

**Polyesters –** Alkyd thermosetting resins characterized by vinyl unsaturation in the polyester backbone. These unsaturated polyesters are most widely used in reinforced plastics. These are the simplest, most versatile, economical, and widely used family of resins. Reinforced matrices can be compression molded, filament wound, continuously pultruded, injection molded, centrifugally cast, corn-formed, and cold molded.

**Post cure –** Additional elevated temperature cure usually without pressure to improve final properties or complete the cure.

**Pot life –** The length of time that a catalyzed resin system retains a viscosity low enough to be used in processing.

**Preform –** A preshaped fibrous reinforcement, of mat or cloth, formed to desired shape on a mandrel or mock-up prior to being placed in a mold press.

**Resin transfer molding (RTM) –** Molding process in which catalyzed resin is pumped into a two-sided, matched mold where fibrous reinforcement has been placed. The mold and/or resin may or may not be heated. RTM offers the ability to consolidate structural parts.

**Sandwich construction –** A structural panel concept consisting, in its simplest form, of two relatively thin, dense, high-strength and parallel sheets of structural material with their faces bonded to and separated by a relatively thick, lightweight core such as honeycomb or foamed plastic.

**Stitching –** A series of stitches embodied in a material such as woven textile fabric.

**Tow –** An untwisted bundle of continuous untwisted filaments. A term commonly used in referring to carbon or graphite fibers.

**Ultimate strength –** The term used to describe the maximum unit stress that a material can withstand when subjected to an applied load in a compression, tension, or shear test.

**Ultrasonic C-scan** – A nondestructive inspection technique for composites in which a short pulse of ultrasonic energy is incident on a sample. Measurement of the transmitted pulse indicates the sample's attenuation of the incident pulse. The attenuation of the pulse is influenced by voids, delaminations, state of resin cure, the fiber volume fraction, the condition of the fiber/matrix interface, and any foreign inclusions present.

**Ultrasonic testing (UT)** – A nondestructive test applied to elastic sound-conductive materials to locate inhomogeneities or structural discontinuities.

**Vacuum-assisted resin transfer molding (VARTM) –** An infusion process by which a vacuum draws resin into a one-sided mold; a cover, either rigid or flexible, is placed over the laminate and taped or otherwise fixed to form a vacuum-tight seal.

**Vinyl ester resins** – A family of resins chemically similar to both unsaturated polyesters and epoxy resins. They were developed as a compromise between the two materials, providing the simplicity and low cost of polyesters and the thermal and mechanical properties of epoxies. Vinyl esters can also be used in wet layups and liquid molding processes such as resin transfer molding.

**Void** – (1) In a solid plastic or laminate, a void is an unfilled space sufficiently large to scatter light. (2) A pocket or gas entrapment within or between the plies of reinforcement.

**Void content** – The percentage of voids in a laminate by volume.

**Waffle core** – A type of sandwich construction containing a deep-drawn third sheet that acts as a core to separate and hold the two face sheets in position.

**Water absorption** – The ratio of the weight of water absorbed by a material to the weight of the dry materials.

**Waviness** – Readily noticeable elevations and/or depressions, including defects such as buckles or ridges.

**Wet layup** – The process of forming an article by first applying a liquid resin to the surface of a mold and then applying a reinforcing backing layer.

**Wrinkle** – A surface imperfection in reinforced plastics where one or more plies of prepreg are formed into a ridge with the appearance of a crease or wrinkle.

**X-ray** – Electromagnetic waves produced by the bombardment of a target with cathode rays.

# INDEX

# PART II:

# REPORT

# SUMMARY: REPORT

After the Cold War, the technology transfer initiatives taken by the federal government to use the unused manufacturing capacities of composite manufacturers in the military and space industries resulted in the proliferation of fiber reinforced polymers (FRP) usage in the bridge industry. Some of these companies capitalized on the potential of the transportation market and were instrumental in advancement of FRP use on bridge structures. Since the 1990s, numerous bridges with FRP decks have been built in the United States, and the number of such bridges is continuously growing as bridge engineers become comfortable with the material and its performance. However, most of these bridge decks have been built using proprietary and/or experimental systems and details. The lack of standardization has been a challenge to bridge engineers, who traditionally are accustomed to standard shapes, sizes, and material properties. In addition, variations in the design and composition of FRP decks have resulted in unique problems and maintenance issues associated with each type, further complicating the upkeep of these decks.

As the usage of FRP decks becomes more widespread, the state DOTs will need to have guidelines and uniform standards to inspect, assess, and evaluate the condition of their in-service FRP deck bridges.

This study was undertaken to help state DOTs and other bridge owners assess the condition of FRP bridge decks in their inventory. This study's goals are (1) to develop recommended uniform guidelines for the inspection and condition evaluation of in-service FRP bridge decks and (2) to develop a course to train bridge inspectors in the methods for inspecting FRP bridge decks. The study is based on state-of-the-art knowledge of FRP material and decks, ongoing research, experiences from state DOTs' experimental FRP deck projects, experiences of the defense and aerospace industries with use of FRP materials, and the state of current practice in the use and assessment of this material in the United States and abroad. The manual and course target the practicing engineer or inspector, and the content and organization of the manual are devised to supplement the existing bridge inspection manuals and courses offered by FHWA.

The research team completed Tasks 1 through 10 of this research project in accordance with the research plan. This final report documents the project and its significant milestones and contains required project deliverables. The appendixes compiled during the report's technology review are available online at trb.org/news/blurb_detail.asp?id=5905 (see p. 163 for a list of appendixes).

# CHAPTER 1

# INTRODUCTION AND RESEARCH APPROACH

The objective of NCHRP Project 10-64, "Field Inspection of In-Service FRP Bridge Decks" (initiated by the project research team on April 24, 2003) was to develop a recommended manual and an inspector's training course for field inspection of in-service FRP bridges. Currently, there are no uniform standards or guidelines for field inspection of in-service FRP bridge decks. As the usage of FRP decks becomes more widespread, state DOTs will need uniform standards to inspect, assess, and evaluate the condition of their in-service FRP deck bridges. This project endeavored to add to current knowledge on FRP decks in order to develop a uniform approach to inspecting, assessing, and evaluating them. The project was accomplished through successful execution of 10 tasks outlined in the project statement. The final report presented herein documents the research program.

## 1.1 BACKGROUND

Historically, composite materials—FRP in particular—have been used extensively in many areas, ranging from highly complex aerospace and military applications to more routine applications such as liquid storage tanks, fishing rods, and truck bedliners. Due to their low weight, high strength, and significant durability advantages, the most prevalent nonconsumer use of FRP material has been in the military aviation and civilian space applications. Although the defense and aerospace industry readily adopted composite materials in the 1960s, it took another 20 years before the bridge industry adopted them as viable alternatives to traditional materials.

One of the earliest uses of FRP materials in a U.S. bridge superstructure commenced in 1994, when Lockheed Martin designed, fabricated, and tested a 30-ft-span, all-composite FRP bridge (*1*). The design effort and subsequent testing program lasted 1 year, and the bridge was eventually installed on a private road at a federal facility in Idaho; instrumentation, testing, and evaluation continued on the bridge. However, the first all-composite-superstructure vehicular bridge on a U.S. public road was installed in 1996 in Russell, Kansas (*2*). Several small-span all-composite bridges have since been built in other states, but the use of all-composite structures has been experimental, and limited to small bridges on lightly traveled rural roads. On the other hand, due to its significantly lower weight and inherent durability advantage over traditional materials such as reinforced concrete, FRP is seeing wider acceptance and use in relatively less critical but maintenance-intensive and dead-weight-sensitive components such as bridge decks.

The number of FRP-decked bridges is continuously growing as bridge engineers become more comfortable with the material and its performance. The lack of standardization, however, has been a challenge to bridge engineers, who traditionally are accustomed to standard shapes, sizes, and material properties. In addition, variations in the design and composition of FRP decks have resulted in unique problems and maintenance issues associated with each type, thereby further complicating the upkeep of these decks.

Most studies and research to date have been focused either on understanding the behavior of FRP decks or on verifying and monitoring in-service performance (*3–8*). However, increased usage of FRP decks will require uniform standards for inspection, assessment, and evaluation of these bridge components (*9*). In the developmental stages of FRP bridge technology, load testing and dynamic response (modal) testing have been used for assessing the condition of FRP decks. Although these methods provide important condition-related information, the information is global in nature and does not provide clues to potential future problems. The relative complexity of the FRP material and its deterioration modes that—unlike those of conventional materials—do not necessarily provide visual clues make the inspection and assessment of FRP decks even more difficult.

It was thought that inspection protocols for bridge decks could be drawn from the aerospace industry, which has made extensive use of FRP composites for decades. However, there are fundamental differences in inspection and maintenance philosophies between the aerospace and highway transportation sectors. Aircraft structures are normally inspected and maintained daily, whereas highway bridges are inspected every 2 years. The differences in inspection frequency and a much more wear-prone application on a bridge make it difficult to use directly the design, inspection, and maintenance philosophies from defense and aerospace industries. In addition, bridge engineers and inspectors are accustomed to working with less fragile materials such as steel and concrete, which show distinct visual clues when they are damaged or deteriorated. Although signs do exist for FRP material condition, the bridge inspectors acquainted with traditional materials have yet to be indoctrinated, and the visual clues are not yet cataloged or adapted for use by the bridge engineering community. As identified by Mertz et al. (*9*), a “lack of easy and reliable inspection and repair procedures” therefore necessitates development of simple indicators and procedures comparable with those that practicing bridge engineers and technicians now use for conventional materials such as steel and concrete.

## 1.2 NCHRP PROJECT STATEMENT AND RESEARCH TASKS

To address the need for practical guidelines in the inspection and assessment of FRP decks, NCHRP developed the following project statement for Project 10-64:

> Guidelines and recommended field procedures for inspection of in-service fiber reinforced polymer (FRP) bridge decks are needed. Inspection and monitoring of FRP structures varies widely, from no monitoring, to visual

> inspection, to experimental NDE techniques. The criteria for field inspection should be based on identification of critical components of FRP decks and determination of critical accumulated damage thresholds in those components. Modal analysis, global inspection techniques, and remote monitoring are already being employed on FRP structures for overall condition assessment. An emphasis on techniques for point damage detection is needed. Other inspection issues include accuracy and reliability requirements for inspection data, continuous versus periodic data collection, depth and frequency of inspection, reliability requirements for equipment and sensors, and calibrating the guidelines with field project data.
>
> In addition, the type of inspection data collected and the recording format varies. As a consequence, it is difficult to compare one project to another. Thus, there is a need for a standard inspection reporting format to make such comparisons possible. Comparative data would also help the composites industry to refine the technology to better meet the states' needs.
>
> The objective of this project is to develop recommended field procedures, evaluation guidelines, and reporting standards for periodic inspection of in-service FRP bridge decks. A training course for FRP bridge deck inspectors shall also be developed.

The project was conducted through execution of the following 10 tasks:

- **Task 1:** Prepare an assessment of performance data, research findings, and other information to determine the failure modes and serviceability problems of FRP bridge decks. Catalog critical details, damage types, and the accumulated damage thresholds for each type of FRP bridge deck. This information shall be assembled from technical literature and from unpublished experiences of engineers, owners, fabricators, and others.
- **Task 2:** Describe the state of inspection practice for FRP bridge decks and identify applicable FRP inspection procedures from other industries. The applicability and effectiveness of visual inspection procedures should be thoroughly evaluated. Documented field performance, especially as it relates to predictions based on the results of current inspection practices, is of particular interest. Field procedures, evaluation guidelines, and reporting standards shall be assessed for speed and economy of use, and for their suitability for integration into the states' bridge inspection programs.
- **Task 3:** Determine suitable inspection procedures for each critical detail, damage type, and deck type identified in Task 1. With an emphasis on point damage

detection, select procedures from those identified in Task 2 based on technical, operational, and economic criteria. Document and justify the reasons for these selections. Clearly identify details, damage types, and deck types for which no suitable inspection procedures exist.

- **Task 4:** Prepare a detailed outline of an inspection manual for FRP bridge decks. The outline shall include recommended record keeping requirements, relevant data items, and a proposed inspection report format.
- **Task 5:** Submit an interim report that documents the results of Tasks 1 through 4. Following project panel review of the interim report, meet with the panel to discuss the interim report and the remaining tasks. NCHRP approval of the interim report will be required before proceeding with the remaining tasks.
- **Task 6:** Develop a draft inspection manual based on the approved outline. The manual shall be prepared in the format used in FHWA's *Safety Inspection of In-Service Bridges: Participant Notebook* (*10*).
- **Task 7:** Develop an instructors guide and appropriate training materials for a course on field inspection and documentation of the condition of FRP bridge decks.
- **Task 8:** Revise the inspection manual, the training guide, and training materials consistent with panel comments.
- **Task 9:** Plan and conduct a pilot training course on FRP bridge deck inspection. The NCHRP will select course participants and provide the facility for the course. The contractor will be responsible only for the cost of training materials and training staff.
- **Task 10:** Submit a final report documenting the research effort. The inspection manual, training guide, and training materials, revised to reflect comments from the pilot training class, constitute appendixes to the report.

## 1.3 RESEARCH APPROACH

In accomplishing the project objectives, the research team believed that adaptation of accumulated inspection experiences and well-served practices from other industries and countries would provide the maximum return for the bridge engineering community. Lessons learned over the past 50 years from the design, inspection, maintenance, and repair of FRP composites in the defense and aerospace industries and experiences with FRP usage in the civil engineering practice provided the basis for selecting methods for inspection and evaluation of FRP bridge decks. In particular, the research team accomplished the project objectives by implementing tasks described in Section 1.4 of this chapter.

The research team conducted a complete technological review to identify the variety of FRP bridge deck problems and their causes. Emphasis was given to identifying the types and composition of FRP bridge decks, common detailing practices, problems associated with each type of bridge deck, and the likely causes responsible for the various problems. In addition, the research team investigated the range of problems associated with FRP components in other countries and industries and identified tested and widely used methods to detect and rectify these problems from the U.S. defense and aerospace industries and in the bridge industry in the United States and abroad. In parallel with the published literature and technology practices research, the research team collected first-hand information, via surveys, on the inspection and evaluation practices and experiences of owners, maintainers, and inspectors of FRP bridge decks. This two-pronged approach allowed the research team to concurrently identify the spectrum of problems and issues associated with FRP bridge decks and to detect potential practices that would be most beneficial for inspection of FRP bridge decks. Based on these findings, an inspection manual and inspectors' training guidelines were developed.

## 1.4 RESEARCH TASKS

The project team has accomplished the following research activities and objectives. The following activities were conducted by the Research Team under each task as listed.

- **Task 1: Prepare an assessment of performance data, research findings, and other information to determine the failure modes and serviceability problems of FRP bridge decks**.
  - A literature search was conducted to acquire reports, papers, guidelines, and other information about FRP material and FRP bridge decks (for a listing, see *Appendix 1: List of Reviewed Literature*). The literature was collected from various sources including the Transportation Research Information Service (TRIS), the Portland Cement Association libraries, FHWA electronic documents, websites, conference proceedings, and others. A databank was created to systematically store the literature search data. In addition, more than 100 electronic documents (reports, manuals or guidelines, and papers) have currently been acquired and saved in a database. The literature search is structured into the following three areas:
    - ➢ *FRP decks and other civil engineering FRP components.* The literature includes information on design, construction, inspection, instrumentation, laboratory testing, and load testing of FRP bridge decks as well as other FRP bridge superstructure members. The literature collected to date covers experiences with FRP bridge components in the United States as well as Europe and Australia. Limited literature on use of FRP in Japan was discovered and is included in the literature database.

  - ➢ *Inspection and assessment of FRP components.* Because limited published literature was available from civil engineering applications, the literature in this area was collected from sources and industries such as the military, aerospace, shipbuilding/naval engineering, pipeline, and industrial applications.

  - ➢ *Damage thresholds and remaining life prediction of FRP components.* The literature in this area was gathered from the defense and aerospace industries and addresses the issues of damage and residual strength of FRP composite components. These data served as a basis for development of a rating procedure.

- – The research team developed a survey questionnaire to obtain unpublished experiences of owners, engineers, fabricators, and maintainers and to obtain specific information on inspection methods and damage types of existing in-service FRP decks (see *Appendix 2: Survey Questionnaire*).

- – The team also conducted targeted telephone interviews using the questionnaire as a standard framework. The survey responses have been divided into the following groups:

  - ➢ *Bridge Owners*: Fifteen state DOTs and one county highway department were contacted by telephone: California; Delaware; Georgia; Indiana; Illinois; Iowa; Kansas; Maine; Maryland; New York; Ohio; Oregon; Pennsylvania; West Virginia; and Wisconsin; and Butler County, Ohio. Of the bridge owners contacted, survey questionnaire responses were obtained from Delaware; Georgia; Illinois; Iowa; Maine; Maryland; New York; Ohio; Oregon; West Virginia; and Butler County, Ohio.

    Bridge plans, details, and inspection records were obtained from Delaware, Illinois, New York, Ohio, and West Virginia. Design plans, inspection reports, and Structural Inventory and Appraisal (SI&A) forms have been obtained on the Muddy Run Bridge in Delaware. Additional information in the form of testing data and construction and inspection photographs are anticipated on this bridge.

    Design plans, construction photos, connection details, and a project report were obtained on one FRP deck bridge in Illinois. Biennial inspection reports on seven FRP deck bridges were obtained from New York. These bridges include Route 46 (Osceola Road) over Salmon River, Route 52 (Triphammer Road) over Conesus Outlet, Route 223 over Cayuga Creek, Route 248 over Bennett Creek, Route 367 over Bentley Creek, Route 418 over Schroon River, and South Broad Street over Dyke Creek.

    From Ohio, a detailed inspection report on the Salem Avenue Bridge was obtained. In addition, design plans and inspection reports were obtained for the Tech-21 Bridge from Butler County, Ohio. Design and inspection reports on the Hanover Street Bridge were obtained from West Virginia.

- ➢ *Bridge Research Community*: To obtain unpublished data on the failure modes and in-service performance of FRP bridge decks, a list of universities conducting research in FRP decks was created. This list was expanded through addition of universities and researchers recommended by the NCHRP panel members. The universities contacted by the research team included Georgia Tech, Iowa State University, University of California at San Diego, University of Cincinnati, University of Delaware, University of Maine, University of Missouri, University of Pittsburgh, University of North Carolina, University of Wisconsin, Virginia Tech, and West Virginia University. In addition, the research team contacted FHWA's Non-Destructive Evaluation (NDE) Center for information on its latest research. The research team has received responses from Georgia Tech, University of North Carolina, and University of Pittsburgh.

- ➢ *Manufacturers and Fabricators*: The research team created a list of FRP deck manufacturers in the United States and has established contact with all major manufacturers to obtain their perspective on in-service behavior of the FRP bridge decks.

- ➢ *International Agencies*: The research team contacted and obtained research and policy reports from two international agencies: Centrum voor Lichtgewicht Constructies TUD-TNO in The Netherlands and The Highway Agency of the Department of Transport in the United Kingdom.

- – Published literature and survey/interview responses were used by the research team to digest information on the current state of the FRP bridge deck inventory as well as the state of inspection practice (for a summary of survey responses, see *Appendix 3: Survey Results*).

- – FRP deck types and manufacturers were cataloged, and details of various deck types identified (for a summary of findings, see *Appendixes 4: Summary of Installed FRP Decks and Their Damage Inspection, Appendix 5: Connection Details and Critical Inspection Points,* and *Appendix 6: Damage Types*).

- **Task 2: Describe the state of inspection practice for FRP bridge decks and identify applicable FRP inspection procedures from other industries.**

  - – An assessment of the current methods of inspection was made.

- **Task 3: Determine suitable inspection procedures for each critical detail, damage type, and deck type identified in Task 1.**
  - A list of potential inspection methods used for inspection of FRP components was created. The inspection methods were gathered from various industries such as aerospace, defense, shipbuilding, pressure vessels, and bridges. The inspection methods' utility was researched and assessed (for a description and discussion of inspection methods, see *Appendix 7: Inspection Methods*).
- **Task 4: Prepare a detailed outline of an inspection manual for FRP bridge decks.**
  - The research team developed an interim inspection manual.
- **Task 5: Submit an interim report that documents the results of Tasks 1 through 4.**
  - An interim project report was prepared and submitted for review.
- **Task 6: Develop a draft inspection manual based on the approved outline.**
  - The research team developed and submitted a draft inspection manual. The manual was based on an outline approved by the NCHRP panel.
- **Task 7: Develop Instructor's Guide Manual.**
  - The research team developed an instructor's guide and a comprehensive training course based on the newly developed manual for inspection and evaluation of FRP bridge decks. An instructors' training presentation was created along with the training course to effectively disseminate the theoretical background and practical aspects of inspection, identification, and evaluation of defects in FRP decks.
- **Task 8: Revise Inspection Manual, Training Guide, and Training Material Manual.**
  - After review of the submitted material by the NCHRP project panel, the research team revised the inspection manual, the training guide, and training material consistent with the panel comments.
- **Task 9: Pilot Training Course Manual**
  - On November 15 and 16, 2004, the team conducted a pilot training course on FRP bridge deck inspection for participants selected by NCHRP. The course included hands-on inspection training with FRP deck samples and visual inspection and nondestructive testing (NDT) techniques, encompassing tap testing, ultrasonic testing, and infrared imaging. The participants were trained

to use the inspection and testing instruments and methods on samples of FRP deck sections brought to the classroom. During the training course, the participants had the opportunity to inspect samples of FRP decks using the various field instruments and assessment and condition evaluation methods described in the training manual. The training course included interpretation of the results and association of the results to the condition assessment and evaluation.

  - Important feedback from inspector trainee participants was solicited through a survey form and question-and-answer sessions. These comments and additional feedback from the research panel provided direction for additional revisions of the draft inspection manual

- **Task 10: Submit Final Report along with the Inspection Manual, Training Guide, and Training Materials Manual.**
  - In accordance with the scope of the project, the research team submitted this final report documenting the research effort. All comments of the NCHRP panel up to and including those generated at the pilot training course were incorporated, and the final revised inspection manual, training guide, and training material are hereby submitted, along with the final report.

## 1.5 REPORT ORGANIZATION

The report is organized into four chapters, a reference section, and appendixes. The chapters synthesize observations and findings; the details of the work, reports, manuals and training materials, task products, collected information, and supporting data are presented in the appendixes, which are published online. The specific sections of the report are as follows:

- **Chapter 1: Introduction and Research Approach.** This chapter provides background information on FRP decks and the current state of knowledge about the decks, the issues that necessitated the implementation of this research project, and the approach and scope of the project.
- **Chapter 2: Findings.** This section presents findings from literature search and the survey of FRP deck owners, inspectors, maintainers, manufacturers, and researchers. In addition, this section presents a summary of findings on critical FRP deck details and methods for inspecting FRP decks.

- **Chapter 3: Interpretation and Applications.** This section presents interpretation of the findings, key issues, applicability of the interpretations to practice, practical considerations, and selection of ideal inspection methods.
- **Chapter 4: Conclusions.** This section presents the conclusions from the research conducted to date and the course of further research that needs to be conducted to accomplish the objectives of this project. Develop a draft inspection manual based on the approved outline.
- **References for Report and Appendixes.** These sections contain the supporting material and other deliverables that form the basis for the content in the chapters of this report. In addition, the appendixes contain detailed sections on inspection of specific types of FRP decks, the inspection manual, and the training guide.

# CHAPTER 2

# FINDINGS

This chapter presents a summary of the research team findings. The findings are based primarily on a survey of the bridge and FRP community, the literature search, the personal experiences of the research team members, and feedback from bridge inspector trainees attending the pilot FRP deck inspector training session.

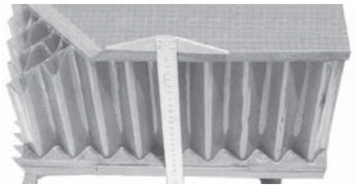
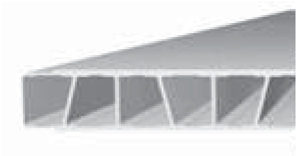
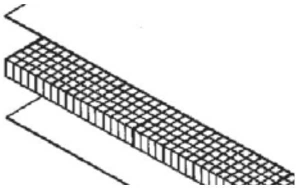
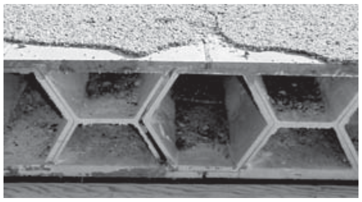
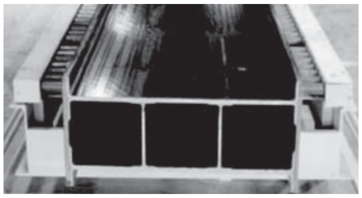
## 2.1 SURVEY FINDINGS

As described in the preceding section, a telephone and mail survey was conducted to obtain both factual and anecdotal information from owners, engineers, inspectors, and researchers on their experiences with design, construction, inspection, and maintenance of FRP bridge decks. All state DOTs and many counties that owned or intended to install FRP bridge decks were contacted during this survey. In addition, almost all major FRP deck manufacturers and many research institutions currently conducting research on FRP decks were contacted during this survey. The survey findings are presented in the sections below.

### 2.1.1 TYPES OF FRP DECKS IN SERVICE

The survey found that there are six major deck types in service at the time of the survey. Each of these deck types has unique cross-sectional geometry, material characteristics, manufacturing processes, and behavior. The deck designs are typically proprietary, and each type of deck is manufactured using specialized material and fabrication methods. The summary of manufacturers, deck descriptions, and cross-sectional views of the deck types is presented in Table 2.1.1-1.

## Table 2.1.1-1 Common FRP Deck Types

| Manufacturer | Deck Description | Number of Bridges | Deck Cross Section |
|---|---|---|---|
| Kansas Structural Composites, Inc. (KSCI) | Sandwich-type deck with top load-bearing skin, bottom sheet skin, and a deep corrugated core. | 12 installations; first in 1996, most recent in 2003. |  |
| Infrastructure Composites, Inc. (ICI) | Same as the Kansas Structural Composites deck. | 1 installation in United States; also in Europe. |  |
| Martin Marietta Composites, Inc. (MMC) | The DuraSpan deck system consists of a trapezoid cross-sectional piece manufactured by the pultrusion process. A DuraSpan deck is post-assembled to delivered width by bonding unit pieces with epoxy or urethane adhesive. | 27 installations; first in 1996, most recent completed in 2004. |  |
| Hardcore Composites, Inc. (HCI) | Hardcore Composites uses various forms of Vacuum-Assisted Resin-Transfer Molding (VARTM ) technology for producing FRP decks. The majority of decks use vertical standing foam boxes as the core and, unlike pultruded decks with fixed patterns and cross sections, the sandwich core pattern in HC decks can vary substantially. | 26 installations; first in 1997, most recent in 2002. |  |
| Creative Pultrusions, Inc. | The Superdeck deck is made with pultruded hexagonal sections bonded to form the desired width of deck and, in many ways, is similar to the DuraSpan deck. | 9 installations; first in 1997, most recent in 2002. |  |
| Strongwell, Inc. | Strongwell is one of the largest pultruders. Although it does not directly market vehicular decks, many pilot composite bridge and deck projects have used Strongwells p ultruded components. | Estimated 3 installations; earliest in 1995 and latest in 2003. |  |

In addition, three other manufacturers or fabricators have provided FRP decks: Fiber Reinforced Systems; Bedford Reinforced Plastics; and Diversified Plastics/Hughes Brothers, Inc. However, for most practical purposes, the six major manufacturers have greater than 95% of the installed base of FRP bridge decks and appear to have established themselves as the suppliers of choice for future installations.

### 2.1.2 CURRENT CONDITION OF FRP DECK INVENTORY

Most FRP vehicular bridge decks in the United States have been in service for a relatively short time, with an average age of less than 5 years. The oldest of these decks were constructed in 1995 and 1996, with a surge in installation activity occurring in 1998 through 2000. Table 2.1.2-1 provides a summary of the temporal distribution of decks installed by the major manufacturers from 1996 through 2004.

**Table 2.1.2-1 FRP Deck Construction over the Years in the United States**

| Manufacturer | Number of Decks Installed in Each Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1996 & Prior | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | **Total** |
| | | | | | | | | | | |
| Kansas Structural Composite, Inc. | 1 | | | 2 | 5 | 3 | | 1 | | *12* |
| Infrastructure Composites, Inc. | | | | 1 | | | | | | *1* |
| Martin Marietta Composites, Inc. | 1 | 2 | | 1 | 2 | 8 | 4 | 6 | 3 | *27* |
| Hardcore Composites, Inc. | | 2 | 3 | 4 | 7 | 9 | 1 | | | *26* |
| Creative Pultrusions, Inc. | | 3 | 2 | 2 | 1 | | 1 | | | *9* |
| Strongwell, Inc. | 1 | 2 | | | | | | 1 | | *4* |
| Others | | | | | | | 2 | 2 | | *4* |
| | *3* | *9* | *5* | *10* | *15* | *20* | *8* | *10* | *3* | ***83*** |

The table demonstrates that although the frequency of FRP deck installations has not been uniform over the years, most of the activity took place in 2000 and 2001 and the average weighted mean of the age of FRP decks is approximately 4 years. Therefore, the FRP deck inventory is expected to be in relatively good condition. However, commonly observed problems or areas of concern noted by bridge owners or practitioners include the following:

- **Joints between FRP deck panels:** Heavy leakage was generally observed at the joint between the FRP deck panels, especially at joint details that did not have special FRP or reinforced plastic strips adhered to the top as well as bottom surfaces of the FRP panels. The leakage typically resulted in corrosion of the steel stringers underneath the FRP deck joints. Inspector attentiveness to panel joints is warranted.

- **Wearing surface:** On several bridges, delamination and debonding of wearing surfaces was noted. Typically, this delamination occurred when thin epoxy overlays were used instead of conventional bituminous overlays as the wearing surface on the decks.

- **Haunch supports:** There was a concern that the FRP deck may not “sit” solidly on the haunch, creating a gap between the bottom surface of the FRP deck and the top surface of haunch, thereby causing impact between the deck and the haunch due to the passage of vehicles.

- **Curbs and parapets:** When curbs, and occasionally parapets, are connected to the deck, the effect on the deck of impact-related damage to the curbs is an issue of concern. The curbs are typically cast-in-place concrete, with the concrete extending into the FRP deck core along a narrow strip of the deck for the length of the parapet or curb.

- **Approach joints:** Approach joints have been known to be critical areas, often requiring innovative details to bridge the transition from the approach to the deck. Where approach joints connect to the FRP deck, the deck edge is stiffened by filling a narrow strip of the porous core of the deck along the width of the approach.

- **Deck to stringer/beam connectors:** Although shear connectors have been used in many FRP deck installations, the details of these connectors have not yet been studied in detail. In some installations, steel clips are used to connect the FRP deck to steel stringers. The general concern regarding clip connections arises due to lack of understanding on the behavior of these joints in practice. Some universities are conducting research on the composite action and effective flange areas of FRP decks and steel stringers. However, current design practice neglects any composite action between the FRP deck and stringers.

- **Delamination of deck components:** On some deck installations, there has been noticeable delamination of the skin sheets from the deck core. This is of significant concern as delamination of deck components can result in an exponential reduction in the stiffness of the deck sections.

- **Moisture ingress:** There have been situations where moisture and water have seeped into the porous core of the deck cross section. Although the FRP material used to manufacture decks is resistant to moisture attack, seepage and the consequent freeze-thaw could result in mechanical damage to the deck, leading to delamination or cracking of FRP deck components.

In summary, due to its relatively young average age, the FRP bridge deck inventory seems to be in good condition. However, there exist some material, fabrication, and detailing issues that are currently affecting the condition of these decks or have the potential to adversely affect the future condition of these decks. These FRP degradation mechanisms serve as the foundation for establishing uniform inspection practice.

### 2.1.3 CURRENT INSPECTION PRACTICE

Key observations based on the survey and interview and inspection reports on the current inspection practice are summarized and presented below:

- **No special inspection guidelines currently exist for inspecting FRP decks.** Only New York State DOT has guidelines (i.e., advisory circulars) on use of FRP on bridge structures that specifically identify the special nature of FRP materials (*11*). However, the guidelines are generally directed toward use of FRP for repair and strengthening of concrete structures.

- **Some DOTs had requested inspection manuals from the deck manufacturers; however, the quality and content of the manuals varied considerably.** In addition, many DOTs have not yet formally accepted the inspection manuals. The research team obtained a more-detailed manual authored by KSCI for three FRP deck bridges in St. James, Phelps County, in Missouri (*12*).

- **Most DOTs do not perform hands-on inspection.** In most states, the current practice seems limited to visual inspection.

- **The DOTs typically use the same rating system as used for other conventional bridge components.** FRP deck rating is currently based on subjective evaluation of the deck appearance.

- **No guidelines currently exist for rating severity of observed conditions on the FRP components.**

- **Most DOTs have performed load testing while some have conducted modal testing of FRP bridge decks.** The testing is usually conducted during the first year and is generally not repeated over an extended period past the first year to 2 years of service. The metric used to evaluate the load-testing observations compares the deflection of the decks during subsequent load tests; no difference observed during subsequent tests indicates satisfactory performance of the deck. However, there does not seem to be a uniform method to evaluate and pinpoint problems if different observations are recorded in subsequent load tests.

- **The tap test is used by some DOTs (California, New York, and Ohio), but many inspection teams are unaware of the methods available and necessary for inspection of FRP components.** Some of the DOTs use the chain-drag method in addition to tap tests to identify locations of delamination (California and New York).

- **Thermography, acoustic methods, and laser shearography have been used on an experimental basis on some bridges,** mostly under University/DOT joint collaboration programs (University of California San Diego, Virginia Tech, and

University of Delaware). It did not appear that any of these methods are being considered for use in the near future by the DOTs.

- **Experimental methods such as impact echo, acoustic emission, radar, and other methods are being tested at university research facilities for potential application in the field.**

## 2.2 FINDINGS FROM THE LITERATURE SURVEY

A detailed and thorough literature search was conducted to obtain as much published information as possible on FRP material and its inspection, with particular emphasis on literature pertaining to FRP bridge decks. Although substantial literature exists on FRP bridge decks, most of it documents field and laboratory tests that focus on mechanical strength and design-related issues (*8, 13,* and *14)*. Some researchers, on the other hand, have conducted research on the durability and environmental stability issues of FRP material as it relates to civil infrastructure use (*1, 7*).

However, most of the research in design, inspection, damage quantification, residual strength, and maintenance of FRP materials has been conducted under the auspices of the defense or aerospace industry organizations. Because FRP materials have been used in U.S. military and space applications for more than 4 decades, considerable information on all aspects—from manufacturing to inspection, maintenance, and repair of FRP components—is available in technical publications issued by the U.S. Department of Defense (*15–20*). A summary of literature reviewed during the course of this research project and its applicability to the objectives of this project is presented in the sections below.

### 2.2.1 HISTORICAL PERSPECTIVE ON FRP USE

The initial research into advanced material technology evolved from metallurgical sciences. The demands of the military and the space industry for cutting-edge applications in the Cold War era resulted in the development of metal composites in the mid-1950s. The following decade saw rapid developments in the field of material engineering, and the development of high modulus boron and graphite filaments in the 1960s initiated an era of non-metallic composite materials (*21*). Chemical industry giants such as Union Carbide and DuPont furthered the development and use of composite materials by designing high-strength, high-modulus carbon, glass, and aramid fibers.

The Department of Defense, the National Aeronautics and Space Administration (NASA), and the research organizations and private-sector industries that fulfilled their needs were among the first to conduct detailed research into FRP materials. The Department of Defense, NASA, and FAA synthesized the applied research conducted by various organizations and converted it into manuals and circulars to codify and transfer the best practices for use in military and aerospace products.

Although the defense and aerospace industries readily adopted composite materials early on, it took another 20 years before the bridge industry started considering FRP as a viable alternative to traditional materials. The first civil engineering application of FRP material was a dome constructed in Benghazi in 1968 (*22*), while the first FRP bridge (pedestrian) was built in Israel in 1975 (*21*). Since then, other countries have experimented with the use of composite materials in bridge construction (*23*). Whereas the U.S. aerospace and military industries were leaders in the use of advanced materials, the U.S. bridge industry lagged behind Europe and Japan (*24*) in adopting the new materials until the 1980s, when FRP materials began to be used in the seismic rehabilitation of bridges. By the late 1980s and early 1990s, the U.S. bridge industry saw many other FRP applications, usually for secondary members on a bridge structure.

One of the first uses of FRP materials in a bridge superstructure was in 1994 when Lockheed Martin designed, fabricated, and tested a 30-ft-span, all-composite FRP bridge (*1*). Design and testing lasted about 1 year, and the bridge was eventually installed on a road at a federal facility in Idaho where field-testing and evaluation continued. This FRP composite deck concept became the basis for designs that are now being successfully produced by MMC.

The first all-composite-superstructure vehicular bridge on a U.S. public road was installed in 1996 in Russell, Kansas (*2, 22*). Several small-span all-composite bridges have since been built in other states, but the use of all-composite structures has been experimental and limited to small bridges on lightly traveled rural roads. On the other hand, due to its significant lower weights and inherent durability advantage over traditional materials such as reinforced concrete, FRP has seen much wider acceptance and use in relatively less critical but maintenance-intensive and dead-weight-sensitive components such as bridge decks.

### 2.2.2 STATE OF RESEARCH AND TESTING OF FRP DECKS

The use of FRP in bridge decks was essentially a result of the technology transfer initiatives taken by FHWA at the end of the Cold War to share and utilize the extensive knowledge base and unused manufacturing capacities of companies traditionally associated with military and space applications. Initiatives by FHWA through the Innovative Bridge Research Program and by other entities interested in furthering the use of FRP in bridge infrastructure resulted in focused study of this material for bridge applications. The research efforts to date have been directed toward developing shapes and sections appropriate for civil applications, developing fabrication methods to manufacture these shapes efficiently, understanding their behavior under simulated vehicular loads, and developing details and methods with which to design and construct FRP decks.

This research therefore has focused on the strength and behavior of FRP bridge decks (*3, 12*), with limited attention directed toward aspects such as serviceability, durability, long-term behavior, post-damage behavior, remaining life, and inspection and maintenance issues. Nearly 100 bridges with FRP decks have been built in the United States since the

1990s, and the number of such bridges continues to grow as bridge engineers become comfortable with the material and its performance. However, most of these bridge decks have been built using proprietary experimental systems and details. The lack of standardization has been a challenge to bridge engineers, who are accustomed to standard shapes, sizes, and material properties. In addition, variations in the design and composition of FRP decks result in unique problems and maintenance issues associated with each type, thereby complicating the upkeep of these decks. Specific knowledge is lacking on issues such as durability, post-damage behavior, unraveling of the composite section, and the effect of environmental factors such as radiation, heat, and moisture. Furthermore, in the absence of well-defined, readily discernible clues to reveal defects and deterioration, indirect means such as load testing have been used to ascertain the adequacy of in-service FRP bridge decks. Bridge owners have undertaken load-testing programs not only to verify the behavior of FRP decks, but also (due to a lack of better condition evaluation options) to ensure that the decks' acceptable behavior will continue over time (*25–28*).

However, the load-testing method has three main drawbacks: (1) the decks are designed with a large factor of safety, so the risk from potential overload is minimal; (2) the design is typically controlled not by strength requirements but rather by deflection limitations, so excessive loads could cause failure due to large deformations; and (3) the failure, if it were to occur, would be non-ductile. Hence in the long-term, visual, or other complementary indicators also must be evaluated to ensure the safety of the decks.

The design assumptions have been verified through load testing and other research, while successive tests of in-service decks have demonstrated that the decks have been behaving as expected. Up to now, and in the absence of better inspection and evaluation methods, successive load testing has provided an indirect method to assess continued good performance of the decks.

### 2.2.3 INSPECTION AND ASSESSMENT OF FRP COMPONENTS

The research on FRP decks has focused mostly on the design, performance, and durability of this material, with limited energy expended on the study of inspection and evaluation methods for these decks (*9*). The survey of the bridge owners and the literature search revealed that bridge owners have usually requested the deck manufacturer to provide inspection and maintenance manuals for FRP decks as part of deck installation projects. In some cases, manufacturers have prepared inspection and maintenance manuals tailored to the specific bridge details and deck type and submitted them as part of the project deliverables (*12*). The survey of bridge owners and maintainers showed that, in many instances, the inspection manuals either were not submitted or were not accepted by the bridge owners; and in some instances, the manuals were found to be of limited use for inspection and maintenance of the decks.

Some bridge owners have, however, developed advisory circulars or internal memos that recognize the special nature of FRP and provide material-specific guidance to help the practicing engineer, inspector, or maintainer manage the FRP infrastructure. Although most bridge owners did not have such memos or guidance documents, two publications by New York State DOT were found to be valuable in this study (*28, 29*).

Unlike the bridge engineering industry, the military and aerospace sectors have used FRP for more than 4 decades. They have conducted extensive research on the inspection and maintenance of this material in order to develop practical procedures that will ensure peak performance of mission-critical FRP components on aircraft and other military structures. They have produced extensive literature on the inspection and evaluation of FRP components in the military and aerospace domains. Although there are fundamental differences in composition, loading, inspection, and evaluation criteria between FRP used in defense or aerospace applications and that used in bridge applications, the basic inspection and evaluation philosophy could be adapted to the bridge industry.

Some publications present practical guidelines and insights on inspection of FRP materials (*20, 30–33*). *Military Handbook 793* (*20*) addresses various inspection methods: visual, acoustic, radiography, ultrasound, and so forth (for detailed discussion, see *Appendix 7*). Inspection and evaluation practices from other non-defense industries provide additional useful insights and tips on practical inspection procedures that could be adopted for inspection of FRP bridge decks (*34–37*).

In addition, state-of-the-art research on inspection and evaluation methods for FRP material—specifically, FRP civil/structural components—will further the current knowledge on inspection methods and help to develop innovative methods suited for the bridge industry. Currently, such research is being conducted in the United Kingdom (*38*), at the U.S. Naval Academy (*39*), and at Virginia Tech (*40*). Additionally, there are many other useful publications that present current research on feasible inspection or evaluation methods for FRP components in civil infrastructures (*41–44*).

Discussion on the applicability of the various inspection methods, the advantages and drawbacks of the methods, and adaptability of these methods into current bridge inspection practice is found in Chapter 3 (also see *Appendix 7*).

### 2.2.4 DAMAGE THRESHOLDS AND REMAINING LIFE PREDICTION

In the civil industry and for FRP decks in particular, research is lacking in the areas of damage estimation, damage accumulation, and remaining life prediction. Some research has been conducted to assess the post-damage behavior of FRP decks (*45*); research in the area of long-term performance and damage accumulation has been restricted to durability testing of FRP material (*1, 7*), and fatigue testing of decks (*46*). The research by Lenett et al. (*45*) studies the effects of damage on the behavior of FRP sandwich deck panels. The research finds that damage, especially delamination, distinctly causes change in the deck stiffness and results in anomalous behavior of the deck. Dutta et al. (*46*) present results from experimental fatigue testing under extreme temperature conditions of different types of FRP and non-FRP decks subjected to 10 million low-cycle fatigue through simulated HS-20 vehicular load. The research focuses on the long-term behavior of FRP decks and shows that behavior of FRP decks is adversely affected by fatigue as well as by higher temperatures. These research studies are limited in their scope, however, and do not provide in-depth insights into the post-damage strength and behavior of FRP decks, nor the effect of damage on the serviceability criteria and useful life of these components. Research on fatigue life of composite beams and civil components has been conducted by Senne (*47*), Tang et al. (*48*), and others.

However, extensive physical research exists in the defense and aerospace industries on damage susceptibility, immediate physical effects of damage, and post-damage behavior of FRP material and components. *Military Handbook 17,* Volume 3 (*17*) is a detailed publication that systematically addresses the issues of damage initiation, damage quantification, correlation of damage to strength, and the ideas the Department of Defense adopted to assess damage and its effect on the performance of the FRP components used in military applications. Other publications provide information on damage initiation and post-damage behavior of FRP (*49–53*). Kan (*49*) presents results from numerous experimental studies on various composite panels to determine the effect of impact damage on the strength of the FRP panels as well as the residual strength of the impacted panels. McGowan and Ambur (*50*) discuss experimental studies on the impact damage and residual strength of composite sandwich panels with and without compression loading. The paper presents correlation between the impact magnitude, the type of impact, damaged area dimensions (damage diameter), and the residual strength of the sandwich panel after the impact. Nyman (*51*) discusses theories and currently used methods for determining damage thresholds in composite materials and enumerates inferences from experimental and analytical studies. The experimental and analytical studies relate to quantification and assessment of damage severity, damage tolerance, and residual strength of composite material used in the development of the new generation of Swedish fighter jet JAS39 Gripen. Tomblin et al. (*52, 53*) meanwhile present a semi-empirical study of impact damage and fatigue tolerance of sandwich airframe structures and provide methodologies in which experimental data could be used to develop damage evaluation criteria.

Extensive studies have also been conducted in the field of analytical assessment and modeling of damage and damage propagation in FRP material. Case et al. (*54, 55*) provide an excellent discussion on practical issues in developing life prediction techniques for FRP material that are typically used in aerospace applications. There are other significant studies that focus on analytical issues in modeling damage, damage propagation, and remaining life of FRP material (*56–60*).

Although most of the research on damage thresholds and residual strength (i.e., remaining life) has been conducted on thin FRP sheet-type or sandwich-type aircraft materials, the defense and aerospace research provides an excellent starting point for extending or extrapolating the findings and philosophies to FRP decks.

## 2.3 KEY PUBLICATIONS

The following publications from the Department of Defense, the U.S. Army Corps of Engineers (USACE), and FAA are promising sources for adapting more than 50 years of industry experience with FRP materials toward bridge engineering applications:

- *Composite Materials Handbook,* Volumes 1 through 5, are military handbooks published by the Department of Defense (*15–19*). Of particular interest is Volume 3, which covers usage, design, and analysis of polymer composite materials. This detailed and comprehensive handbook covers almost all aspects of composite behavior and provides practical insight on the damage etiology and accumulated damage thresholds of FRP materials. In addition, the handbook provides practical guidelines on identifying defects, damage, and deterioration of FRP components.

- *Nondestructive Active Testing Techniques for Structural Composites* is another military handbook published by the Department of Defense (*20*). This handbook provides detailed discussion and practical application guidelines for the complete range of NDT techniques—from visual inspection to the more complex nuclear radiography methods—which could be used on FRP materials. The handbook also discusses the reliability of the various methods and provides an in-depth assessment of the techniques, including the correlation of specific NDT methods to type of defects and type of FRP design.

- Engineering Technical Letter ETL 1110-2-548, "Engineering and Design: Composite Materials for Civil Engineering Structures," is published by USACE (*33*). The ETL compiles and discusses various issues in the use and upkeep of composite materials for civil engineering applications. This 60-page document covers all aspects of FRP material used in civil engineering structures—manufacturing to durability, quality assurance, and inspection and repair.

- *Advisory Circular AC20-76: Maintenance Inspection Notes for Boeing B-707/720 Series Aircraft* and *Advisory Circular AC20-107A: Composite Aircraft Structure,* published by FAA (*31, 32*), provide practical advice and inspection methods for various FRP components of the Boeing 707 aircraft. These circulars, and similar circulars and directives for other aircrafts, provide invaluable practical advice on identifying and appraising damage and defects in structural components made of FRP materials. The practical aspects of the inspection techniques and damage detection and appraisal methods identified in these circulars could easily be adapted for application on bridge structures.

- *Structures Design Advisory: FRP Decks and Superstructures*, an informative advisory circular published by New York State DOT (*11*), alerts bridge designers and inspectors to the unique characteristics of FRP material and provides guidance on how to work with this material.

- *Laboratory and Field Testing of FRP Composite Bridge Decks and FRP-Reinforced Concrete Bridge for the City of St. James, Phelps County, MO,* a report published by Missouri DOT (*12*), includes typical details as well as inspection and maintenance manuals for three FRP bridge decks constructed and monitored within the scope of the research project.

- "Inspection of FRP Equipment: When and How to Inspect and What to Look For," a paper published by TAPPI (*37*), provides some practical guidelines on inspection of FRP components.

- "Fatigue Performance Evaluation of FRP Composite Bridge Deck Prototypes Under High and Low Temperatures," a paper presented at the 82nd Annual Meeting of the Transportation Research Board in 2003 (*46*), provides experimental data and inferences from the experimentation to assess the fatigue characteristics of FRP decks. A Master's Thesis titled "Fatigue Life of Hybrid FRP Composite Beams" and published by Virginia Tech (*47*) provides some excellent data on fatigue characteristics of FRP beams. "Fatigue Model for Fiber-Reinforced Polymeric Composites in Civil Engineering Applications," a research report published also by Virginia Tech (*48*), provides useful data, interesting inferences, and analytic models on the fatigue life of FRP materials used in civil infrastructure applications.

- "Simulation of Performance and Life Prediction for Composite Laminates: MRLife12" (*55*), a software program and its manual published by Virginia Tech, provides an excellent discussion on developing analytical residual strength or remaining life models based on experimental data and analytical concepts. *Enhanced Reliability Prediction Methodology for Impact Damaged Composite Structures,* published by FAA (*49*), provides data on strength reduction due to various types of damages on various types of FRP materials. The data from this research could be useful to devise a statistical semi-empirical method that other industries could use to gage the severity of damage and its likely effect on the material's post-damage performance.

# CHAPTER 3

# INTERPRETATION AND APPLICATIONS

This section presents interpretation of the findings, key issues, applicability of the interpretations to practice, practical considerations, and selection of ideal inspection methods.

## 3.1 ISSUES WITH DESIGN VARIANTS

The large variability in types of FRP decks and the lack of standardization in deck shapes, material composition, manufacturing processes, design methods, and details are important issues that affect the inspection, maintenance, and management of the FRP deck inventory in the United States. Since FRP is a “designed” material, its characteristics are significantly affected by parameters such as the composition and layout of its constituent parts, manufacturing processes, shapes of the cured FRP subcomponents, the process used in assimilation of subcomponents, and the geometry of the final deck cross section. Therefore, changes in any of these parameters can create innumerable types of FRP decks, each with distinct characteristics and associated strengths and weaknesses.

This variety of FRP deck types raises several key issues that are relevant to the current study. These issues are briefly discussed below:

- **Difficulty in establishing a uniform quality and performance standard for FRP decks:** Due to the variety of materials and manufacturing processes, it is difficult to establish uniform quality and performance standards for the FRP decks. Each “type” of deck differs from the others in its constituent materials, subcomponents, and method of manufacturing, leading to variations in achievable quality, consistency of quality, and the performance and behavior of the decks. For example, the consistency and quality achievable through the pultrusion process is reportedly much higher than that achievable through the hand lay-up process. Similarly, the type of component materials used—that is, the fiber and the resin—and the cross-section geometry—for example, sandwich-type with vertical corrugated core, bonded pultruded sections, and so forth—will significantly affect behavior and performance.

- **Potential for variability in types and location of critical details:** Due to variability in the internal construction of FRP decks, there is considerable latitude for variability in the location of critical details. For example, in sandwich panels, critical locations that can show delamination or separation are typically at the core–to–face sheet connections while in pultruded sections, the critical locations could be at joints between each pultruded subcomponent. In addition, the corrugated core in some sandwich-panel decks is bonded to the face sheets along thin edges, creating potentially weak areas that can easily separate due to poor adhesion or load-deflection effects.

- **Potential for superfluous changes leading to development of newer deck designs:** Without established guidelines, designers and manufacturers have the freedom to vary any aspect of FRP material, section, or manufacturing method. This can result in development of superfluous variations in deck type, each slightly different from the other and each with different performance and behavior patterns. This practice could result in unnecessarily large variety of decks without any real benefit in terms of better design or performance, leading to difficulty in maintaining or managing such deck inventory.

- **Difficulty in expeditiously assimilating and distributing critical information about new design should be anticipated:** Although it is possible to catalog critical areas and peculiarities of each given deck, each new deck type introduced into the bridge inventory will require careful evaluation and study by the bridge owner to identify the critical details and vulnerable areas in the new deck type. In addition, this ever-changing information will have to be collected, analyzed, composed, and disseminated at regular intervals to practicing engineers, inspectors, and maintainers in order to keep them up-to-date on the vulnerabilities and issues of each deck type.

- **Inadequate testing and performance assessment:** The research team feels that the ease with which deck types can be changed may lead to creation and installation of future FRP decks without the rigorous testing and assessment that is now common. Such inadequate testing and assessment could result in installation of decks whose behavior is not clearly understood and whose critical details or vulnerable locations are not clearly identified, potentially causing serviceability and safety problems in the future.

## 3.2 ISSUES WITH CURRENT INSPECTION PRACTICE

The current inspection practice ranges from no inspection of the FRP deck to detailed inspection that includes visual inspection, tap testing, load testing, modal testing, and thermography.

Among participants in the bridge owner group, the survey found limited awareness of the FRP decks' uniqueness or their need for special methods and activities for inspection and maintenance. Some survey participants were unaware of the need to check for simple visual clues such as discoloration or cracking or acoustic clues such as hollow sounds to detect delamination. From the survey, it appears that most personnel involved with the design of FRP decks appreciated the need for addressing special inspection and maintenance issues regarding such decks; however, personnel not involved in the design and those responsible only for deck inspection or maintenance seemed to consider these decks similar to conventional concrete decks in their inspection and repair needs. Very few of the survey participants seemed to employ FRP deck–specific inspection methods while inspecting their FRP deck inventories.

Most survey participants from the academic and consulting group and some from the owner group were aware of the FRP decks' uniqueness and their need for special methods for inspection, assessment, and maintenance. Many among these survey participants were aware of more-detailed inspection methods such as ultrasonic, radiographic, and thermographic methods. It was also discovered that some of these nonstandard techniques, such as ultrasonic and thermographic methods, were being evaluated through joint owner-academic research projects.

Based on these findings, the research team sees a clear and definite need for education and training of bridge inspectors and maintainers as to the unique nature of FRP decks and methods to inspect and evaluate these decks.

## 3.3 CLASSIFICATION OF SIGNIFICANT DETAILS

Given many types of bridge decks—each with distinct material characteristics, fabricating methods, cross-sectional details, and performance characteristics—the research team recommends organizing the inspection instructions by the deck or manufacturer type. Because critical areas and inspection methods differ for each deck type, it makes practical sense to organize the data by deck types. Doing so serves two purposes: (1) it makes it easy for inspectors to select an appropriate checklist of details to inspect and (2) it allows inspectors to choose appropriate inspection methods and evaluation criteria.

For each deck type, an ideal method to organize the data for inspection and evaluation of the FRP decks is by dividing the deck details into two major categories: those associated with the deck cross section and those associated with bridge geometry and connections.

- **Category 1: Details within the deck cross section:** Significant details in this category include those that are associated with cross-section design, material, manufacturing, and fabrication of deck panels. The significant details within this category generally depend on the material components, manufacturing and fabrication process, and cross-section composition of the deck.

- **Category 2: External details and connections:** In this category, details related to entities external to the deck cross section are included. Some of these entities include wearing surfaces, connections between deck panels, connection of deck panels to the superstructure and substructure, and connection details of the parapets and railings to the deck or other superstructure elements. The significant details in this category are not necessarily associated with a specific type of deck, but are more globally applicable.

Various commonly observed damage types associated with these significant details have been identified (see *Appendixes 4–6*). The damage types are organized first by deck types and then into the two categories identified above. In addition to cataloging the damage types, an attempt has been made, where possible, to correlate the damage type to the type of loading or affecting medium that may have contributed to the cause or exacerbation of the damage. The common causative agents for most damage types included type of loading, restraint conditions, impact effects, and fire and temperature effects, among others. (For a summary of the findings, see *Appendixes 4–6.)*

## 3.4 INSPECTION METHODS, THEIR APPLICABILITY, COSTS, AND OTHER ISSUES

Inspection methods that could be used for FRP decks were identified from the realms of aerospace, defense, shipbuilding, pressure vessels, and bridges. (See *Appendix 7* for descriptions and discussions of inspection methods and inspection cost data.) Some of these methods, such as visual or UT methods, are similar to those used currently in bridge inspection. Other methods such as acoustic, laser shearography, radiography, thermography, and so forth are more complicated and seldom used in current bridge inspection programs. In Table 3.4-1, the various inspection methods are presented in order of complexity and usefulness and are correlated to the types of defects or deck components that these methods assist in detecting.

**Table 3.4-1 Inspection Method Applicability for Specific Defects and FRP Deck Features (*20*)**

| Features and Anomalies<br>Technique | Foreign Matter | Impact Damage | Cracks | Delaminations | Disbonds | Core or Internal Elements | External Elements |
|---|---|---|---|---|---|---|---|
| Visual | X | X | X | | | | X |
| Mechanical Impedance (Tap Test) | | X | | X | X | X | X |
| Thermal | | | X | X | X | | |
| Ultrasonic | | | | X | X | X | X |
| Acoustic Emission | | | X | X | X | | |
| Radiographic | X | | X | | | X | X |
| Laser Shearography and Other | | | X | X | X | X | |

The visual method is by far the most important and simplest technique for inspection of FRP decks. Even in the aerospace and defense industries, inspectors rely on the visual technique for detecting in-service problems. Visual inspection allows the inspector to rapidly detect gross imperfections or defects such as cracks, delamination, or impact damage. Visual inspection often can aid in detecting other imperfections such as porous adhesive fillets, lack of filleting, lack of adhesive, edge voids, discoloration, deformation, and other imperfections. To a trained inspector, the visual technique provides immediate clues, and this method serves as the mechanism for identifying areas that should be inspected through other more-detailed and complex methods. Although this technique is operator-interpretive, it is of such significant value that the inspectors should be trained to know what they are looking for and what any variation might mean to the strength and reliability of the component. The visual method, however, has two drawbacks: (1) it does not lend itself to quantifying the extent of damage and (2) components within another component or not directly visible can not be inspected by this method.

Tap testing is another excellent and easy method for inspecting FRP decks. The tap test allows the inspector to notice changes in sounds emitted while tapping FRP surfaces. Although this method lends itself more readily to inspection of sandwich panels, it can nevertheless be used on pultruded sections, albeit with lesser degree of effectiveness in detecting delaminations or debonds. However, most common problems on FRP decks can be identified by using the tap-test method in conjunction with the visual technique.

Neither of these techniques requires any specialized equipment, and both are easy to incorporate into a bridge owner's inspection program through training in inspection of FRP components. On the other hand, some of the other techniques listed above are much more complex, are significantly more costly and time-consuming, and require special expertise in conducting the tests and in interpreting the results. Except for thermography, most of the specialized methods are useful only for inspecting small areas due to cost and operational reasons. Therefore, these methods are more practical for detailed assessment of potentially damaged or defective areas that have already been identified by either the visual or the tap-test methods.

Of the various advanced methods, thermography and UT appear to be most practical in terms of their applicability and adoptability in a bridge owner's inspection program. Bridge engineers and inspectors already familiar with UT equipment and technique would find it easy to adapt this method for use on FRP decks. The thermography method also could be readily adopted into an inspection program because it is somewhat easier to use, does not require very expensive equipment, and provides output that can be visually analyzed. The other techniques, such as radiography and shearography, are more costly and often require expensive specialized equipment and considerable training to operate the equipment and interpret the results. Hence, these other techniques, although useful and applicable, appear less likely to be incorporated into the current bridge inspection programs.

## 3.5 DETAILS AND DESIGNS THAT WILL BE DIFFICULT TO INSPECT

As discussed in the previous section, numerous methods are available to inspect critical details and detect defects or damage in FRP bridge decks. The research team feels that visual and tap-test methods can provide satisfactory results in detecting defects and damages at most locations on FRP decks. Specific areas identified by the visual or tap test techniques that require further in-depth investigation can then be inspected using advanced techniques such as thermography, radiography, or UT. Although some of these methods detect damage that generally cannot be detected by visual or tap-test methods, they cannot necessarily detect damage in every location on the deck. In some areas of the deck, none of the current methods is effective in detecting and assessing the extent of damage.

Based on evaluation of all the in-service FRP decks, it appears that some Category 1 details, such as the core or the web elements, are the most difficult details to inspect. Due to the nature of the deck cross section and the layout of deck sub-components, the region of deck cross section between the top and bottom surfaces or face sheets is not visible for visual inspection. Although the tap test can detect damage such as delaminations or disbonds, this detection is limited to areas close to the top and bottom surfaces of the decks; in most cases, even the top surface of the deck is not accessible due to the presence of thick overlays.

Among the types of defects, disbonds between the core and the top face sheet in sandwich-type decks are probably the most difficult to detect. Based on findings on the Salem Avenue Bridge, it appears that the core–to–face sheet connection in sandwich-panel decks is vulnerable to disbond due to the small edge area along which the core section is adhered to the face sheets. Even advanced methods like radiography are probably not effective for detecting this defect unless the X-rays are taken in the horizontal plane and in proximity to the defect. Any defect in the core that would be visible to a radiograph in the plan view would therefore be easier to detect than a defect that would be visible in a cross-sectional view. In the case of core–to–top face sheet disbond, modal testing methods or other methods such as impact echo or impulse response may provide a solution in detecting such damages.

In pultruded decks, web and flange (top and bottom surfaces) are created concurrently in the pultrusion process, and the sections do not have any discontinuity between the core elements (or web elements) and the flanges. Also, since pultrusion is an automated process, the quality of the pultruded product is likely to be uniform and consistent as compared with sandwich construction in which semi-automatic or manual processes typically are used. Thicker elements and robust sections in this type of deck, however, make it less responsive to tap tests. In addition, this type of deck has similar inspectability issues as the sandwich decks except that the likelihood of defects in this type of deck could be better controlled as compared with sandwich decks.

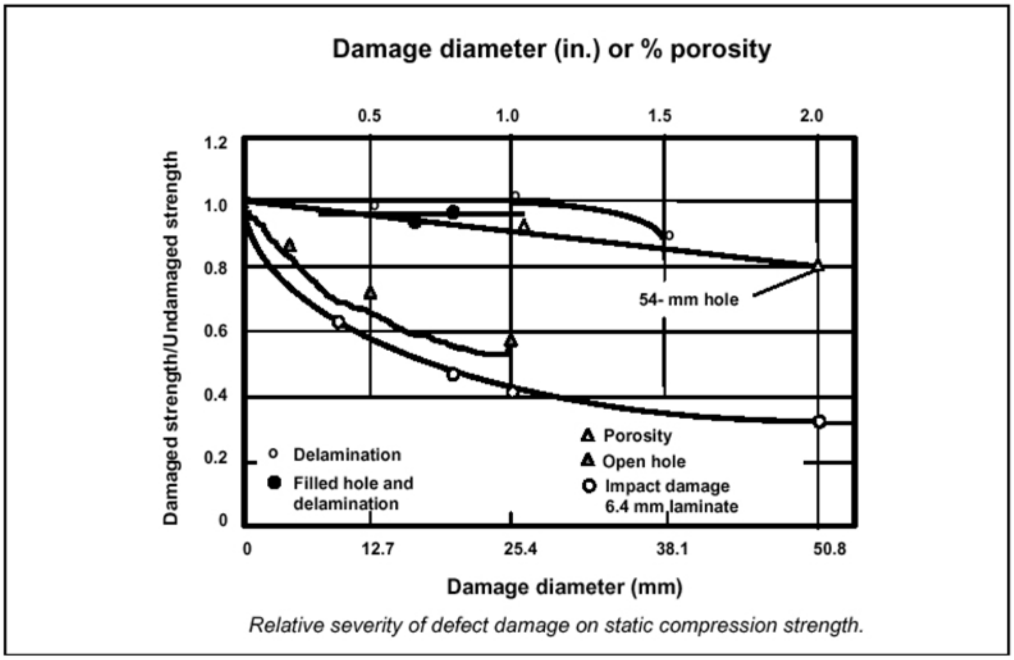
Although there are some significant details in FRP decks that seem to create inspectability issues, the research team feels the existence of any such damage or defect would lead to other signs such as larger deflections, discolorations, dimpling, stretch marks, and so forth that would alert the inspector to the existence of problems. (Further discussion on significant details, inspection methods, and difficult-to-inspect areas of each of the major deck types is presented in *Appendixes 4* and *7*.)

## 3.6 INFERRING AND INTERPRETING INSPECTION RESULTS

Inferring and interpreting inspection results is one of the most important aspects of productively using inspection data to ensure safety and serviceability of inspected components. In the case of FRP bridge decks, once the damage or defects are identified and categorized, they will have to be evaluated and assessed based on some form of uniform rating system. The research team believes that for Category 2 significant details—which include connections, overlays, joints, and so forth—of the assessment could be made using a hybrid method that draws on guidelines used for conventional bridge components combined with those for FRP elements.

However, for Category 1 significant details—that is, details internal or intrinsic to the FRP deck cross section—of a system will have to be developed that will correlate observed damage to reduction in remaining life of the components. Although it is difficult to quantify the somewhat subjective inspection data from visual observations or acoustic tests, the aerospace and defense industries have developed methods to quantify some of these results. Based on the type of defect and magnitude of damage, the severity and potential for failure due to the damage are evaluated using a uniform scale in military and aerospace applications. This approach to evaluating damage on composite aircraft structure and components is based on extensive experimental and theoretical studies. For example, one of the charts developed from these studies (*17,* Figure 7.3.2 [a]) is reproduced below in Figure 3.6-1. As observed in Figure 3.6-1, the chart allows one to correlate the extent of damage (diameter of hole or extent of delamination, etc.) to the reduction in load-carrying capacity of the components, thereby allowing for a systematic evaluation of damage with respect to the reduction in strength.

Although the chart is designed for aircraft structures, it shows that a workable systematic approach does exist for assessment of FRP field inspection data. It should be noted, however, that these charts in the military handbooks and other aerospace references have been developed from more than 50 years of research, testing, and development, and it is unlikely that similar charts could be developed for the bridge engineering industry within the scope of this project. In addition, aircraft structures are inspected at very high frequency, typically before and after each flight. However, it is possible to borrow the idea from the defense industry to establish a long-term goal of developing similar charts for the bridge industry.



*Relative severity of defect damage on static compression strength.*

**Figure 3.6-1 Damage versus Strength Reduction (*17*, Figure 7.3.2[a]).**

The research team developed a semi-empirical method that would assist an inspector in evaluating and assessing the damage and deterioration based on some uniform or standard scale. This correlation of damage or deterioration to remaining life either could be set arbitrarily or could be devised using some of the test data from aerospace applications. For example, for a specific type of deck, the extent of damage quantified by the delaminated area could be related to specific reduction in strength. The scale was set such that at one end, for no delamination, there would be no reduction in carrying capacity of the deck while a delamination diameter of twice the deck thickness or half the clear span of the deck could be attributed to loss of, say, 50% of the strength.

# CHAPTER 4

# CONCLUSIONS

The research conducted under NCHRP Project 10-64 has developed recommended uniform guidelines for inspection and condition evaluation of in-service FRP bridge decks and developed and implemented the pilot session of a course to train bridge inspectors on the methods of inspecting these bridge decks. The study is based on current state-of-the-art knowledge on FRP material and decks; ongoing research; experiences of bridge owners, maintainers, fabricators, and designers; knowledge from the defense and aerospace industries; and the state of current practice in the use and assessment of this material in the United States and in other countries.

Information in support of this research was gathered primarily through two sources—published literature and the unpublished accounts and experiences of owners, inspectors, practicing engineers, researchers, and others associated with FRP material in general and FRP decks in particular. The collected information was used in conjunction with the experiences of the research team members to develop practical insights into the current state of inspection practice, inspection requirements, and inspection and assessment methods for FRP bridge decks.

Based on the research, the key conclusions made by the research team are summarized below:

- **Due to the relatively young age of the FRP bridge deck inventory, the decks are currently in good condition in general.** Many of these bridge decks have been instrumented and monitored, and most have undergone load tests at regular intervals for 2 or more years after construction. However, on some isolated bridge decks, problems have been observed, prompting extensive evaluation and remedial activities.

- **Awareness regarding the unique nature of FRP decks is lacking** when compared with decks and components made of conventional construction materials. Therefore, the need for FRP-specific inspection requirements continues.

- **In addition to the inspection manual, future development of analytical rating and maintenance guidelines for FRP decks and components is warranted.**

- **The many commercial variants of FRP bridge deck types in service today make it more challenging to design, build and maintain FRP deck types.** Because technical innovation and competitiveness will continue, new design and fabrication and construction methods will proliferate, perhaps causing some of the existing systems to become obsolete. Therefore, the research team urges that AASHTO, state highway departments, and the funding agencies maintain efforts like this one to create and communicate relevant guidelines and other information related to design, manufacture, construction, inspection, and maintenance of FRP bridge decks.

- **The research team has identified crucial performance details for each major type of FRP deck design.** These details have been classified into two categories, one specific to the details within the deck sections and the other containing details associated with connections and other locations external to the deck cross section. The visual and tap-test methods are presently the most suitable techniques for inspection of FRP decks. Other advanced methods should be used to perform more-detailed investigations and structural evaluations after specific areas of interest are identified through visual or tap-test techniques.

- **The research team found that limited data were available for quantifying the severity and criticality of defects.** Most of data and research in this area have been restricted to military and aerospace research with almost no systematic studies conducted for FRP bridge decks. The research team developed a semi-empirical scale for assessing the severity of defects and damage in FRP decks by using experiences from other industries. The research team compiled this knowledge base on inspection of FRP deck while performing Tasks 1 through 5 and used it to develop the inspection manual and training course.

- **In addition to those discussed above, the research team has discovered knowledge gaps in the state-of-the-art research.** The research team feels that the variety of deck designs has contributed significantly to the creation of these knowledge gaps. Specific research is limited in the following areas and needs to be initiated:

    - Fatigue, durability, and the effect of environmental loads on FRP decks.

    - Damage initiation and propagation in FRP decks. This type of data is particularly important for assessing deck sections near curbs, railings, and other connection areas where there is high probability for impact and damage.

    - The post-damage behavior, remaining strength, and remaining life of FRP decks. Although such studies have been conducted in the defense and aerospace industries, the studies have not yet been extended to civil engineering applications.

- Composite action or the effect of composite action on FRP decks. Many FRP decks have been constructed with deck-to-stringer connection details that foster composite action and therefore should be studied to understand the effect of composite action on the FRP deck.

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# APPENDIXES FOR REPORT

The following appendixes are not published herein but are available online at trb.org/news/blurb_detail.asp?id=5905:

- *Appendix 1: List of Reviewed Literature*
- *Appendix 2: Survey Questionnaire*
- *Appendix 3: Survey Results*
- *Appendix 4: Summary of Installed FRP Decks and Their Damage Inspection*
- *Appendix 5: Connection Details and Critical Inspection Points*
- *Appendix 6: Damage Types*
- *Appendix 7: Inspection Methods*
- *Appendix 8: Manual for Inspection of In-Service FRP Bridge Decks*
- *Appendix 9: Assessment of Likelihood of Damage Progression*
- *Appendix 10: Training Guide and Presentation for Manual for Inspection of In-Service FRP Bridge Decks*

*Abbreviations and acronyms 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 |
| ADA | Americans with Disabilities Act |
| 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 |
| DHS | Department of Homeland Security |
| DOE | Department of Energy |
| EPA | Environmental Protection Agency |
| 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 |
| ISTEA | Intermodal Surface Transportation Efficiency Act of 1991 |
| ITE | Institute of Transportation Engineers |
| NASA | National Aeronautics and Space Administration |
| 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 |
| SAFETEA-LU | Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005) |
| TCRP | Transit Cooperative Research Program |
| TEA-21 | Transportation Equity Act for the 21st Century (1998) |
| TRB | Transportation Research Board |
| TSA | Transportation Security Administration |
| U.S.DOT | United States Department of Transportation |